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Permeable pavement combined

Page Contents

Permeable pavement combined

This document combines several documents related to permeable pavement. Individual documents can be viewed by clicking on the appropriate link below. Fact sheets are not included in this combined document.

Porous pavement articles

Overview

Green Infrastructure: Permeable pavement can be an important tool for retention and detention of stormwater runoff. Permeable pavement may provide additional benefits, including reducing the need for de-icing chemicals, and providing a durable and aesthetically pleasing surface.

Example of a new retrofit permeable parking lot at the University of Minnesota

Permeable pavements allow stormwater runoff to filter through surface voids into an underlying stone reservoir where it is temporarily stored and/or infiltrated. The most commonly used permeable pavement surfaces are pervious concrete, porous asphalt, and permeable interlocking concrete pavers (PICP). Permeable pavements have been used for areas with light traffic at commercial and residential sites to replace traditionally impervious surfaces such as low-speed roads, parking lots, driveways, sidewalks, plazas, and patios. While permeable pavements can withstand truck loads, permeable pavement has not been proven in areas exposed to high repetitions of trucks or in high speed areas because its' structural performance and surface stability have not yet been consistently demonstrated in such applications.

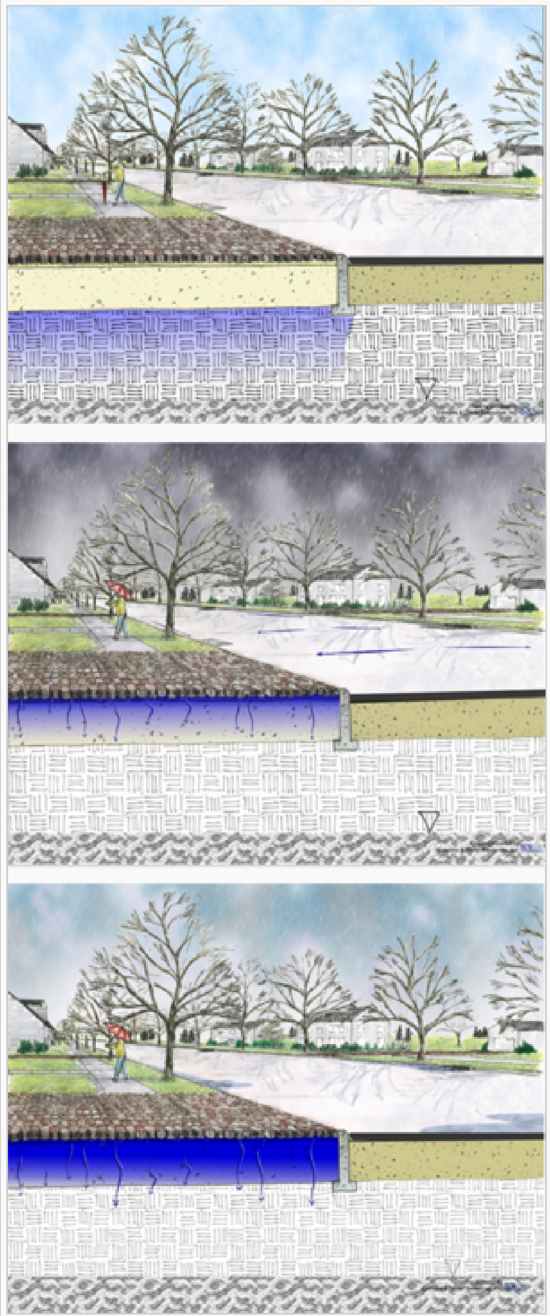
While the designs vary, all permeable pavements have a similar structure, consisting of a surface pavement layer, an underlying stone aggregate reservoir layer, optional underdrains, and geotextile over uncompacted soil subgrade. From a hydrologic perspective, permeable pavement is typically designed to manage rainfall landing directly on the permeable pavement surface area. Permeable pavement surface areas may accept runoff contributed by adjacent impervious areas such as driving lanes or rooftops. Runoff from adjacent vegetated areas must be stabilized and not generating sediment as its transport accelerates permeable pavement surface clogging. Additionally, the capacity of the underlying reservoir layer limits the contributing area.

Benefits and limitations

- **Benefits**: Permeable pavements allow conversion and/or design of typical impervious areas (i.e. parking lots) to pervious areas that infiltrate stormwater runoff. When compared to typical impervious areas, properly designed and maintained permeable pavements can reduce the runoff quantity, reduce total suspended solids (TSS) and total phosphorus (TP) loads into receiving water bodies, and reduce runoff temperatures. In addition, permeable pavements can reduce nitrogen, metals and process oils. Permeable pavements are well suited for high density urban areas with limited space for other BMPs such as ponds, swales or bioretention systems.
- **Limitations**: As with all BMP's, permeable pavement has limitations that need to be considered before design and construction. Limitations are discussed in detail in the permeable pavement design section.

Pretreatment considerations

Pretreatment that removes sediment from runoff draining onto permeable pavement from impervious surfaces is desirable since sediment can clog permeable pavements. For that reason, pretreatment areas should emit practically no sediment onto the permeable pavement surface. Locating such areas next to impervious surfaces upslope from the permeable pavement may not be possible on some sites. Permeable pavement itself can be considered a pre-treatment device and included in a stormwater treatment train if underdrains are utilized within the storage reservoir. The underdrains will typically be routed to a bioretention area.



Permit applicability

Permeable pavements can be utilized to assist in meeting stormwater requirements for volume, total suspended solids, and total phosphorus. The section on credits provides guidance on the implementation of permeable pavements that may be utilized to meet various runoff volume and pollutant runoff reduction goals.

Retrofit suitability

In most cases, existing impervious surfaces can be replaced with permeable pavements to achieve improved runoff conditions. Retrofit requires the removal of the old pavement and subgrade and the installation of the underlying reservoir layer and the permeable pavement. For the greatest water quality credits, avoid compaction of subgrade soils. If this is not possible, compacted subgrade soils should be removed or loosened to achieve the maximum infiltration rate possible.

Cold climate suitability

Favorable permeable pavement performance has been documented in cold climates. Air in the aggregate base acts as an insulating layer and the higher latent heat associated with higher soil moisture delays the formation of a frost layer while maintaining permeability and this condition also reduces frost depths when frozen. Winter sanding should be avoided when possible and if used, removed by vacuuming the following spring. Permeable pavements require significantly less use of, or in some cases, no deicing chemicals and sand to maintain a safe walking or driving surface. Other climate considerations include high wind erosion (California 2003). Dramatic reductions in life span of the infiltration properties of the pavement may occur in

these areas due to particulate clogging and this may require additional surface vacuum cleaning.

Schematic showing the process of infiltration into permeable pavement during and after a rain event. Note how infiltrating water includes precipitation falling directly on the pavement and runoff from the adjacent street directed onto the pavement. Caution should be used when runoff is diverted from impervious surfaces to permeable pavement.

Special receiving waters suitability

Many of the same design considerations and limitations apply to permeable pavement as to other infiltration practices.

- Infiltration of runoff from hotspots (e.g., gas stations, chemical storage areas, etc.) should be carefully considered and in many cases avoided.
- Special consideration also needs to be taken near wellhead areas and basement foundations.
- Some designs may require consideration of storms in excess of the infiltration capabilities of the pavement. For these situations the design should ensure the excess runoff does not negatively impact special surface waters (e.g.,trout streams) through the implementation of additional BMPs.

Water quality

In general, permeable pavement provides removal of TSS and other pollutants through processes similar to other filtration and infiltration BMPs. However, permeable pavements are not suggested for areas that may receive high loading rates of TSS due to their propensity for surface clogging. The expected annual volume and pollutant reductions for designs without an underdrain are a function of the underlying reservoir storage volume. The greater the storage volume, the greater the annual volume and pollutant reductions.

For designs with underdrains, reductions are typically lower depending on the drain outflow location that determines the volume of water removed by the underdrains before infiltration. Of the water intercepted and draining through the underdrain, 45 percent (with upper and lower 90 percent confidence bounds of 65 percent and 24 percent, respectively) of the total phosphorus and 74 percent (with upper and lower 90 percent confidence bounds of 93 percent and 33 percent, respectively) of total suspended solids removal can be expected. These event mean averages and ranges are derived from a literature review on research on permeable pavements. The literature includes 19 studies on pollutant reductions and 10 studies on volume reductions. (See the section on credits for more information on pollutant reduction credits and their relationship to the MIDS credit calculator).

Water quantity

The primary advantage of permeable pavements is providing volume reduction by reducing runoff from a site and/or providing attenuation from outflows. The volume of water that will be reduced during a given rainfall event will be equivalent to the volume available for storage below the pavement or underdrain (if an underdrain is present). More discussion on this item is available in the section on credits.

Types of permeable pavement

Green Infrastructure: Permeable pavement can be an important tool for retention and detention of stormwater runoff. Permeable pavement may provide additional benefits, including reducing the need for de-icing chemicals, and providing a durable and aesthetically pleasing surface.

Photo illustrating pervious concrete. Pervious concrete is a special type of concrete with a high porosity that allows water from precipitation and other sources to pass directly through.

The most commonly used permeable pavement surfaces are pervious concrete, porous asphalt, and permeable interlocking concrete pavers. Other options include plastic and concrete grids, as well as amended soils (artificial media added to soil to maintain soil structure and prevent compaction) (MPCA 2008). This document focuses on pervious concrete, porous asphalt and permeable interlocking concrete pavements. A general comparison of their properties is provided in the table below. Additional requirements specific to each system should be obtained by designers from suppliers and from the local review authority.

For each of the above pavement surfaces, there are many variants depending on the design goals. For instance, permeable pavement can be installed with a deep underlying reservoir consisting of open-graded, crushed rock. This design provides water quality and quantity control by storing runoff and infiltrating it into the subgrade soils over an extended period of time. A second design variation includes a deep underlying reservoir consisting of open-graded, crushed rock above an impermeable layer of soil or a liner and an underdrain. The underdrain typically discharges to a stormwater pond or storm sewer system. This design provides some runoff flow attenuation, filtering, but no volume reduction. These two options provide different levels of treatment.

To assist with selection of a permeable pavement type, a general comparison of the properties of the three major permeable pavement types is provided in the table below. Designers should check with product vendors and the local review authority to determine specific requirements and capabilities of each system. Schematic cross sections of each system are illustrated in the design section for permeable pavement.

Photo illustrating porous asphalt. Porous asphalt is standard hot-mix asphalt that allows water to drain through it.

Summary of properties of permeable pavements.
Link to this table

Properties	Pervious concrete	Porous asphalt	PICP
Typical pavement surface thickness[a]	5 to 8 inches	3 to 4 inches (thicker for high wheel load applications)	3 inches[a]
Bedding layer[a,f]	None	1 in. AASHTO No. 57 stone	2 inches of AASHTO No. 8 stone (MnDOT 3127 FA-3)
Reservoir layer[b,f]	AASHTO No. 57 stone or per hydraulic design	AASHTO No. 2, 3, or 5 stone	4 inches of AASHTO No. 57 stone over No. 2, 3 or 4 stone
Construction properties	• Cast in place • Seven day cure • Must be continuously covered	• Cast in place • 24 hour cure	• No cure period • Manual or mechanical installation of pre-manufactured units
Installed surfacing cost[c]	3 to $4/square foot	$2/square foot	3 to $4/square foot
Minimum batch size	None		
Longevity[d]	20 to 30 years		
Overflow	Catch basin, overflow edge, elevated underdrain		
Runoff temperature reduction	Cooling at the reservoir layer		
Surface colors/texture	Range of light colors and textures	Black or dark grey colors	Wide range of colors, textures and patterns


Photo illustrating permeable interlocking concrete pavement. Permeable interlocking pavers consist of concrete or stone units with open, permeable spaces between the units.

Load bearing capacity[e]	Handles all vehicle loads with appropriate surface and base/subbase layer material and thickness design		
Surface cleaning[g]	Periodic vacuuming; replace if completely clogged and uncleanable		Periodic vacuuming; replace jointing stones if completely clogged and uncleanable
Other issues	• Avoid concentrated deicers • Avoid winter sanding	• Avoid seal coating • Avoid winter sanding	Avoid winter sanding
Design reference	Report 522-2010	Hansen 2008NAPA	Smith 2011 ICPI

[a]Thickness may vary depending on site and traffic conditions

[b]Reservoir storage may be augmented by corrugated metal pipes, plastic arch pipe or plastic lattice crates

[c]Supply and install minimum surface thickness only; minimum 30,000 sf with Minnesota 2012 prevailing labor wages. Does not include base reservoir, drainage appurtenances, engineering, or inspection

[d]Based on pavement being properly maintained. Resurfacing or rehabilitation may be needed after the indicated period

[e]Depends primarily on on-site geotechnical considerations and structural design computations

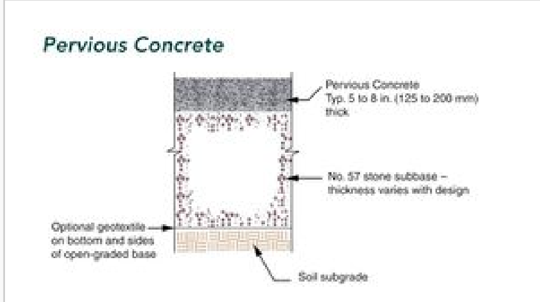
[f] ASTM D448 Standard Classification for Sizes of Aggregate for Road and Bridge Construction or ASASHTO M-43

[g]Periodic vacuuming frequency determined from inspection, intensity of use, and other potential sediment sources

Design criteria for permeable pavement

Green Infrastructure: Permeable pavement can be an important tool for retention and detention of stormwater runoff. Permeable pavement may provide additional benefits, including reducing the need for de-icing chemicals, and providing a durable and aesthetically pleasing surface.

This section provides information on design considerations, criteria and specifications for permeable pavement. Base/subbase thickness is determined for water storage using hydrologic sizing and/or dynamic modeling over time. Base/subbases thickness for supporting traffic is determined using structural design methods. The thicker of the two resulting designs is employed.



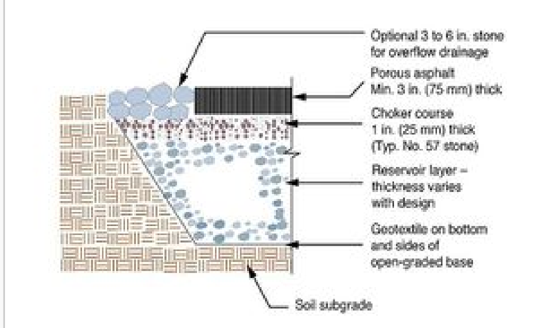
Schematic illustrating typical pervious concrete cross section and basic components of a pervious concrete system.

Hydrologic design considerations

Permeable pavement is subject to the following design considerations, including benefits and constraints.

- Available space – A significant advantage of permeable pavement is its ability to combine detention/ infiltration and pavement, thereby reducing or eliminating land required for detention facilities. This is especially important in urban areas with high land prices and highly developed sites with little or no space for stormwater detention.
- Soils – Soil conditions and infiltration rates determine the use of an underdrain. (NRCS Hydrologic Soil Group (HSG) C or D soils usually require an underdrain, whereas HSG A and B soils often do not.) Designers should evaluate existing soil properties during initial site layout with the goal of configuring permeable pavement that conserves and protects soils with the highest infiltration rates. In particular, areas of HSG A or B soils shown on soil surveys should be considered as primary locations for all types of infiltration practices.

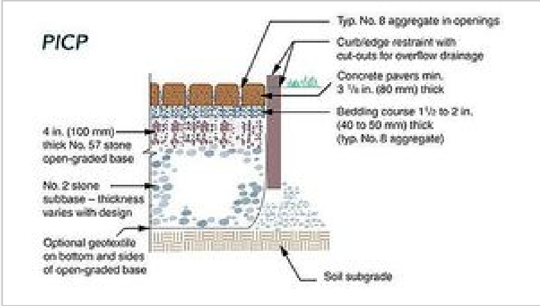
  Soil surveys and HSG classifications provide a general estimate of the soil's infiltration rate. Soil infiltration rates can also be estimated from soil classifications per ASTM D2487. However, it is best to determine rates using on-site infiltration testing per ASTM D3385 Standard Test Method for Infiltration Rate of Soils in Field Using Double-Ring Infiltrometer, D5093 Standard Test Method for Field Measurement of Infiltration Rate Using Double-Ring Infiltrometer with Sealed-Inner Ring or other available methods. The median rate determined from in-situ measurements should be reduced by a factor of 2.5 and this reduced value used in design calculations. This reduction accounts for incidental compaction during construction and sedimentation of the subgrade over time.



Schematic illustrating typical porous asphalt cross section and basic components of a pervious concrete system.

Information: The safety factor of 2.5 is greater than a factor of 2 recommended in most guidance for permeable pavement (see [1], [2], [3], [4], [5]). This manual utilizes recommended soil infiltration rates for hydrologic soil groups (see [6]). These are not as conservative as infiltration rates based on the Unified Soil Classification System, particularly for finer textured soils. We therefore recommended the more conservative value of 2.5

In most cases, permeable pavement should not be situated above fill soils. Designs in compacted fill soils may require an impermeable liner and an underdrain. Permeable pavements should only be placed on fill soils when laboratory tests indicate the compacted fill will be stable when saturated and that slope stability of deep fills has been verified by a geotechnical engineer.



Schematic illustrating typical permeable interlocking concrete pavement cross section and basic components of a pervious concrete system.

- Geotextiles - In the absence of full-depth concrete curbs or impermeable liners, geotextiles are recommended on the (vertical) sides of permeable pavements to separate the reservoir layers from the adjacent soil subgrade. Horizontally placed geotextiles between the aggregate base and soil subgrade are at the option of the designer. Geotextile use should be carefully evaluated and selection should be guided by AASHTO M-288 Geotextile for Highway Applications (AASHTO 2010). Specific selection guidance is provided under the Subsurface Drainage section. Class II geotextiles are generally used.
- Contributing drainage area – Permeable pavements sometimes capture runoff from adjacent areas, pavements, and roofs. Runoff from permeable areas is not recommended due to potential clogging of the permeable pavement. The at-grade contributing drainage area into permeable pavement should generally not exceed twice the surface area of the permeable pavement. This guideline helps reduce the rate of surface sedimentation. The 2:1 ratio can be increased to no greater than 5:1 if at least one of these conditions exists:
  - permeable pavement is receiving runoff from roofs as it tends to be very low in sediment; or
  - runoff from adjacent impervious surfaces remains unburdened with sediment due to effective pre-treatment prior to entering the permeable pavement.

For more information on contributing area, see Contributing drainage area to stormwater BMPs.

> **Caution:** Permeable pavement and contributing impervious pavements are assumed to receive regular vacuuming to reduce and control sediment loads and surface clogging potential.

- Soil subgrade slope – The slope of the soil subgrade should be as flat as possible (i.e., less than 1 percent longitudinal slope) to enable even distribution and infiltration of stormwater. Lateral slopes should be less than 1 percent. Steep slopes can reduce the stormwater storage capacity of permeable pavement. Designers should consider using a terraced subgrade design for permeable pavement in sloped areas, especially when the subgrade slope exceeds 3 percent.
- Soil subgrade compaction – This should be avoided wherever possible to maximize infiltration. In some situations, compaction may be needed for supporting vehicular loads. In such cases, compaction density and subsequent soil infiltration should be assessed in a test pit(s) on the site to determine an acceptable soil density and its contribution to soil strength and infiltration. The measured infiltration rate for use in hydrologic calculations may be reduced by the designer to compensate for long-term sedimentation on the soil subgrade.

- Excavation methods - Excavation should be conducted in a manner that minimizes soil subgrade compaction. Tracked rather than wheeled equipment is recommended working from the sides of the excavation. For larger projects, excavation can create cells and berms where equipment removes soil from one area or cell while positioned on higher soil around each cell (see Construction specifications for permeable pavement). Other techniques include ripping or loosening soils compacted by construction equipment. This can be done with the teeth on excavation equipment buckets. Compaction of the aggregate base into these areas is especially important since scarified soil can settle and be reflected on the surface.
- Surface slope – Surface slopes for all permeable pavement types should be at least 1 percent to provide an alternate means for drainage should the surface become completely clogged due to lack of maintenance. Designs should provide an alternate means for stormwater to enter the aggregate reservoir if the pavement surface should ever become clogged, or for extreme storm events. For pervious concrete and porous asphalt without curbs, this can be a 2 foot wide stone edge connected to the reservoir. For curbed pavements, inlets may be used.
- Overflow structures – Permeable pavements are not designed to store and infiltrate all stormwater from all storms. Therefore, an outlet or outlets are required to prevent water from rising into and over the surface. One type of outlet control would be a catch basin with an internal weir and low-flow orifice. The catch basin can also handle runoff from the surface should it become clogged.
- Minimum depth to seasonal high water table – A high groundwater table may cause seepage into the bottom of permeable pavement and prevent complete drainage. Also, soil acts as a filter for pollutants between the bottom of the pavement base and the water table. Therefore, a minimum vertical separation of 3 feet is required between the bottom of the permeable pavement reservoir layer and the seasonal high groundwater table. For systems with impermeable liners, a minimum of one foot clearance is Highly recommended between the liner and the seasonal high water table.
- Setbacks – To avoid harmful seepage, permeable pavement should not be hydraulically connected to building foundations unless an impermeable liner is placed against the foundation or basement wall. Even under these circumstances, great care should be taken to avoid creating a wet basement problem. If there is no liner, the permeable pavement base should be 10 feet or greater from structures (EPA recommends a minimum setback from building foundations of 10 feet down-gradient and 100 feet up-gradient. See EPA factsheet “Storm Water Technology Fact Sheet: Porous Pavement,” EPA 832-F-99-023). Again, it is the designer’s responsibility to avoid creating a wet basement problem. Likewise, permeable pavement bases should be hydraulically separated from adjacent road bases.

  Permeable pavements without underdrains infiltrate stormwater and should follow requirements for wellhead protection (EPA recommends a minimum setback of 100 feet from water supply wells). Underground utility lines are best located away from permeable pavement bases. However, if they need to penetrate the base, consideration should be given to waterproofing (depending on the utility) or possible encasement using low-strength flowable concrete fill. Setbacks can be reduced at the discretion of the local authority for designs that use underdrains and/or liners.

- Informed Owner – The property owner should clearly understand the unique maintenance responsibilities inherent with permeable pavement, particularly for parking lot applications. The owner should be capable of performing routine and long-term actions (e.g., vacuuming) to maintain the pavement’s hydrologic functions, and avoid future practices (e.g., winter sanding, seal coating or repaving) that diminish or eliminate them. For porous asphalt a diluted emulsion fog can be used as needed. Maintenance agreements, covenants, maintenance easements or performance bonds are encouraged between the local authority and the property owner.

Green Infrastructure: Permeable pavement can be used at highly developed urban sites that have little or no space retention.

Caution: The required setback distance to a municipal water supply well is 50 feet, but it is recommended that permeable pavements be a minimum horizontal distance of 100 feet from any municipal water supply well

Warning: A minimum vertical separation of 3 feet is required between the bottom of the permeable pavement reservoir layer and the seasonal high groundwater table (saturated soil) or the top of bedrock (i.e. there must be a minimum of 3 feet of undisturbed soil beneath the infiltration practice and the seasonally high water table or top of bedrock).

- Limitations – There are several limitations for use of permeable pavement, as summarized below.
  - Permeable pavements should not be used in high pollutant loading sites. High pollutant loading sites are those that receive constant sediment or trash and/or debris. Places where fuels and chemicals are stored or handled can be potential stormwater hotspots and permeable pavement should not be constructed in these places. Likewise, areas subject to wind borne dust and sediment should not use permeable pavement unless the pavement can be vacuumed regularly. The following limitations should be considered before utilizing permeable pavements in any design.
  - Permeable pavement is suitable for pedestrian-only areas, low-volume roads, low speed areas, overflow parking areas, residential driveways, alleys, and parking stalls. These can be residential collector roads or other applications with similar traffic loads.
  - Permeable pavement can be prone to clogging from sand and fine sediments that fill void spaces and the joints between pavers. As a result, it should be used carefully where frequent winter sanding is necessary because the sand may clog the surface of the material. Periodic maintenance is critical, and surfaces should be cleaned with a vacuum sweeper at least two times a year.
  - Fuel may leak from vehicles and toxic chemicals may leach from asphalt and/or binder surface. Porous pavement systems are not designed to treat these pollutants.

Design criteria

Base/subbase thickness is determined for support traffic using structural design methods and for water storage using hydrologic sizing and/or dynamic modeling over time. The thicker of the two resulting designs is used.

Structural design

The structural design process for supporting vehicles varies according to the type of pavement selected. The pervious concrete industry is in the process of developing ASTM test methods for characterizing compressive or flexural strengths of pervious concrete. These tests are needed to model fatigue under loads. As an interim step, fatigue equations published by the American Concrete Pavement Association (ACPA 2010) assume such

inputs to be comparable in nature (but not magnitude) to those used for conventional concrete pavements. The ACPA design method should be consulted for further information as well as pervious concrete industry software. General guidelines for pervious concrete surface thickness are published by the National Ready Mix Concrete Association NRMCA and the Portland Cement Association (Leming 2007).

Porous asphalt (Hansen 2008) and permeable interlocking pavements (Smith 2011) use flexible pavement design methods adopted from the 1993 AASHTO *Guide for Design of Pavement Structures* (AASHTO 1993). In addition, MnDOT design methods, approved mechanistic principles, and manufacturer's specific recommendations should be consulted.

There has been limited research on full-scale testing of the structural behavior of open-graded bases used under permeable pavements to better characterizing relationships between loads and deformation. Therefore, conservative values (i.e., AASHTO layer coefficients) should be assumed for open-graded base and subbase aggregates in permeable pavement design.

Regardless of type of permeable pavement, structural design methods consider the following in determining surface and base thicknesses to support vehicular traffic:

- pavement life and total anticipated traffic loads expressed as 18,000 pounds equivalent single axle loads or ESALs (This method of assessing loads accounts for the additional pavement wear caused by trucks.);
- soil strength expressed as the soaked California Bearing Ratio (CBR), R-value or resilient modulus (Mr);
- strength of the surfacing, base and subbase materials; and
- environmental factors including freezing climates and extended saturation of the soil subgrade.

Soil stability under traffic should be carefully reviewed for each application by a qualified geotechnical or civil engineer and lowest anticipated soil strength or stiffness values under saturated conditions used for design. Structural design for vehicular applications should generally be on soil subgrades with a CBR (96-hour soaked per ASTM D 1883 or AASHTO T 193) of 4 percent, or a minimum R-value = 9 per ASTM D 2844 or AASHTO T-190, or a minimum Mr of 6,500 pounds per square inch (45 Mega Pascals) per AASHTO T-307. Soils with lower strengths typically require thickened permeable bases or those using cement or asphalt stabilized open-graded aggregates per Mn/DOT Pavement Manual, Section 3-3.01.02 Treated Base.

Soil compaction required to achieve these soil strengths will reduce the infiltration rate of the soil. Therefore, the permeability or infiltration rate of soil should be assessed at the density required to achieve one of these values. If soils under vehicular traffic have lower strengths than those noted above, or are expansive when wet, there are several options, including

- underdrains;
- thickened base/subbase layer(s);
- cement or asphalt stabilized base layers; and
- lime or cement stabilized (with design consideration given to practically no infiltration in such cases).

These options are typically used in combination. Pedestrian applications can be placed on lower strength soils than those noted.

Pedestrian applications can be placed on lower strength soils than those noted.

Outflow rate and volume through underdrains

If the depth of the base/subbase for the full infiltration system is excessive, because, as an example, the design subgrade soil infiltration rate is not adequate to remove the water from the design storm within the designated period of time, then the design should include underdrains. The following procedure is for sizing the base/subbase for partial infiltration designs (i.e. contains underdrains).

The outflow rate from underdrain(s) can be approximated by

$q_u = k x m$

where

q_u = outflow through underdrain, feet/hour
k = Coefficient of permeability for each 6 inch diameter underdrain, feet/hour
m = underdrain pipe slope, feet/feet

This equation is based on Darcy's Law, which summarizes several properties that groundwater exhibits while flowing in aquifers. Although the hydraulic conductivity (measure of the ease with which water can move through pore spaces of a material) of the aggregate subbase is very high (approximately 17,000 feet per day or 8,500 inches per hour), the discharge rate through underdrains is limited by the cross sectional area of the pipe. As the storage volume above/around the underdrain(s) decreases (i.e., the hydraulic head or water pressure decreases), the base/subbase and in turn the underdrain(s) will drain increasingly slower. To account for this change in flow conditions within the subbase and underdrain(s) over time, a very conservative coefficient of permeability (k) of 100 feet per day per pipe can be used to approximate the average underdrain outflow rate.

Once the outflow rate through each underdrain has been approximated, the depth of the base/subbase needed to store the design storm can be determined by

$d_p = N(d_c R + P – ((i/2)t_f) – q_u (T_{fill})) / n$

where

N = number of underdrain pipes
d_p = the depth of the reservoir layer (feet);
d_c = the depth of runoff from the contributing drainage area (not including the permeable paving surface) for the design storm (feet);
R = A_c/A_p The ratio of the contributing drainage area (A_c, not including the permeable paving surface) to the permeable pavement surface area (A_p);
t_f = the time to fill the reservoir layer (day) – typically 2 hours or 0.083 day;
P = the rainfall depth for the Treatment Volume (1.1 inch), or other design storm (feet);

i = field-verified infiltration rate (ft/day); and
n = porosity (cubic feet/cubic feet)

To estimate the number of underdrain pipes (N), take the dimension of the parking lot in the direction the pipes are to be placed and divide by the desired spacing between pipes – round down to the nearest whole number.

With full infiltration systems, the maximum allowable drain time (d_{max}) needs to be calculated to make sure the stored water within the base/subbase does not take too long to infiltrate into the soil subgrade. However, for partial infiltration systems, there is a second method of storage water discharge, namely the underdrains. The depth and number of underdrains are variables that can be adjusted (unlike the infiltration rate into the soil subgrade) so that the actual drain time equals or is less than the maximum allowable drain time. If the discharge of the underdrains is included, then

$d_{max} = fT_s+ q_uT_1 N / V_r = d_p$

Rearranging the previous equation, the storage time during which the water is at or above the underdrain(s) (hours) is given by

$T_1 = ((V_rd_p) – (fT_s)) / (q_u N)$

The elevation of the pipe above the soil subgrade is then given by

$d_{below} = f(T_s – T_1) / V_r$

where

T_1 = the storage time (hours) during which the water is at or above the underdrain(s); and
d_{below} = depth (feet) of the subbase below the underdrains.

Permeable pavement can also be designed to augment detention storage needed for channel protection and/or flood control. The designer can model various approaches by factoring in storage within the base/subbase, expected infiltration and any outlet structures used as part of the design.

Once runoff passes through the surface of the permeable pavement system, designers should calculate outflow pathways to handle subsurface flows. Subsurface flows can be regulated using underdrains, the volume of storage in the reservoir layer, the bed slope of the reservoir layer, and/or a control structure at the outlet.

Design for nutrient and TSS reductions

Permeable pavements can be designed to reduce nutrient loadings to the ground or surface waters. The design needs to be specifically designed to capture phosphorus. The permeable pavement system can also be designed to capture nitrogen, although it is important to note that nitrogen and

phosphorus each require specific designs to facilitate their removal from stormwater. The following paragraphs describe the design characteristics necessary for the removal of phosphorus and nitrogen.

A study by (Bean, 2007a) showed higher nitrate concentrations in the exfiltrate compared to the infiltrate. Nitrogen reduction capabilities of permeable pavement can be enhanced in partial infiltration designs that detain water in the base/subbase for over 24 hours. This time is required to ensure complete de-nitrification occurs.

PICP can use specially coated aggregates in the joints and bedding and all systems can use them in the base to reduce phosphorous. Coated aggregates (sometimes called "engineered aggregates") have an effective life of seven to ten years and target the removal of dissolved phosphorous, according to manufacturer's literature.

A filter layer made of sand or fine aggregate placed under or sandwiched within permeable pavement bases are occasionally used as a means to reduce nutrients. This layer can be enhanced with iron filings for phosphorous reduction (Erickson 2010). Their effectiveness, initial cost, reduction in flow rates, and maintenance costs should be weighed against other design options for nutrient reductions. Sand filters will incur additional construction expense and this can be reduced by placing sand filters under the subbase at the down slope end of a permeable pavement. The disadvantage of sand filters is that they will eventually require removal and restoration if continued phosphorus reduction credit is desired. Concentrating their location in the down slope areas of the site can help reduce future maintenance costs and site disruptions.

A second approach useful for nutrient and TSS reduction can occur on sloping sites by creating intermittent berms in the soil subgrade. These enable settlement of suspended solids and encourage de-nitrification if appropriately designed. A third alternative is using a "treatment train" approach where a permeable pavement initially filters runoff and the remaining water outflows to bioswales or rain gardens adjacent to the pavement for additional processing and nutrient reduction. There may be additional BMPs used to remove nutrients as the water moves through the watershed.

Soil infiltration rate testing

Prior to infiltration testing, soil borings should be taken with an auger to assess the consistency of the soil type and horizons. Guidance for conducting infiltration tests and for determining the number of borings can be found here.

Conveyance and overflow

Permeable pavement designs should include methods to convey larger storms (e.g., 2-year, 10-year) to the storm drain system. The following is a list of methods that accomplish this.

- Place a perforated pipe horizontally near the top of the reservoir layer to pass excess flows after water has filled the base. The placement and/or design should be such that the incoming runoff is not captured (e.g., placing the perforations on the underside only). Pipe placement should be away from wheel loads to prevent damage.
- Increase the thickness of the top of the reservoir layer.

- Create underground detention within the reservoir layer of the permeable pavement system. Reservoir storage may be augmented by corrugated metal pipes, plastic or concrete arch structures, etc.
- Route excess flows to another detention or conveyance system that is designed for management of extreme event flows.
- Set the storm drain inlets level with the elevation of the permeable pavement surface to effectively convey excess stormwater runoff past the system. The design should also make allowances for relief of unacceptable ponding depths during larger rainfall events.

Reservoir layer

The reservoir below the permeable pavement surface should be composed of clean, washed crushed stone aggregate and thickness sized for both the storm event to be stored and the structural requirements of the expected traffic loading. The recommended minimum void ratio should be 40 percent per ASTM C29. Reservoir base layers for pervious concrete are typically washed AASHTO No. 57 stone and those for porous asphalt are AASHTO No. 2, 3, or 5. PICP uses AASHTO No. 2, 3, or 4 stone.

If exposed to vehicular loads, all crushed stone should be Minnesota Department of Transportation (MnDOT) Class A or B coarse aggregate, minimum 80 percent crushed, typically granite, basalt, gneiss, trap rock, diabase, gabbro, or similar material. The maximum Los Angeles Rattler Loss should be 35 percent per AASHTO T-96 and no greater loss than 10 percent per AASHTO T-104 Magnesium Sulfate Soundness Test on the non-igneous portions and as modified by the MnDOT Laboratory Manual (MNDOT 2005). Limestone aggregates not meeting these requirements are not recommended in vehicular applications. Class C and D aggregates may be used in areas subject only to pedestrian traffic.

Underdrains

Underdrains install quickly when placed on or in the soil subgrade, surrounded by stone base materials. The outflow portion at the end is not perforated and is raised to a designed height that allows for some water detention prior to outflow. Placement at this elevation also protects the pipe with aggregate during base compaction. For permeable pavement bases/subbases using 2 or 3 inch maximum size aggregates, underdrain pipes with them should be surrounded with at least 4 inches of ASTM No. 57 (maximum 1 inch size aggregate) to protect the pipes during compaction. An underdrain(s) can also be installed and capped at a downstream structure as an option for future use if maintenance observations indicate a reduction in the soil permeability.

Maintenance

Proper maintenance of permeable pavement is crucial for ensuring its longevity and functionality. Some portions of the maintenance plan require planning during the design stages. These items are noted below.

- Observation Well – Typically this consists of a well-anchored, six-inch diameter perforated PVC pipe that extends vertically to the bottom of the reservoir layer. This is installed at the down slope end of the permeable pavement. The observation well should be fitted with a lockable cap installed flush with the ground surface (or under the pavers) to facilitate periodic inspection and maintenance. The observation well enables visual monitoring of drawdown within the reservoir layer after a storm.

- Overhead Landscaping – Some communities require a certain percentage of parking lots to be landscaped. Large-scale permeable pavement should be carefully planned to integrate landscaping in a manner that maximizes runoff treatment and minimizes risk of sediment, mulch, grass clippings, crushed leaves, nuts, and fruits inadvertently clogging the surface. Prior to construction, owners should commit to a vacuuming plan that includes vacuuming frequency and equipment needs. The vacuuming frequency typically depends on the time of year. In the spring, tree buds and seeds necessitate frequent vacuuming. In the fall, tree leaves and acorns necessitate frequent vacuuming. In the summer, vacuuming frequency depends on permeable pavement exposure to organic material from trees and nearby vegetated areas. Vacuum equipment and methods for sediment removal are provided in the section addressing operation and maintenance.

Major design elements

The following design elements apply to permeable pavement.

Minimum separation distance

Warning: It is *REQUIRED* that infiltration practices be designed with a minimum vertical distance of 3 feet between the bottom of the infiltration practice and the seasonally high water table or bedrock layer. See also Step 8 under the Design procedures section.

Local authorities may require greater separation depths.

It is *HIGHLY RECOMMENDED* that infiltration practices not be hydraulically connected to structure foundations or pavement, to avoid seepage and frost heave concerns, respectively. If groundwater contamination is a concern, it is *RECOMMENDED* that groundwater mapping be conducted to determine possible connections to adjacent groundwater wells.

Setback distances

Warning: The minimum setback distance from a stormwater infiltration system to a public water-supply well is 100 feet for wells classified as sensitive and 50 feet for all other public supply wells, as *REQUIRED* by the Minnesota Department of Health. See MDH isolation distances (pollutant or contaminant that may drain into the soil)

Caution: The minimum setbacks in the table below are *HIGHLY RECOMMENDED* for the design and location of infiltration practices. It will be necessary to consult local ordinances for further guidance on siting infiltration practices.

Required and recommended minimum vertical and horizontal separation distances. This represents the minimum distance from the infiltration practice to the structure of concern. If the structure is above-ground, the distance is measured from the edge of the BMP to the structure. If the structure is underground, the vertical separation distance represents the distance from the point of infiltration through the bottom of the system to the structure, while the horizontal separation (often called setback) distance is the shortest distance from the edge of the system to the structure.
Link to this table

Structure		Distance (feet)	Requirement or recommendation	Note(s)
Vertical	Saturated soil	3	Requirement[1]	
	Bedrock	3	Requirement[1]	
Horizontal	Public supply well	100 for sensitive wells; 50 for others	Requirement	
	Building/structure/property line[2]	10	Recommended	
	Surface water	none unless local requirements exist		If nearby stream is impaired for chloride, see [7]
	Septic system	35	Recommended	
	Contaminated soil/groundwater			No specific distance. Infiltration must not mobilize contaminants.
	Slope	200	Recommended	from toe of slope >= 20%
	Karst	1000 up-gradient 100 down-gradient	Requirement[1]	Active karst

[1] Required under the Construction Stormwater General Permit

[2] Minimum with slopes directed away from the building

Karst: It is *HIGHLY RECOMMENDED* that infiltration practices not be used in active karst formations without adequate geotechnical testing.

Wellhead Protection Areas: It is *HIGHLY RECOMMENDED* to review the Minnesota Department of Health guidance on stormwater infiltration in Wellhead Protection Areas.

Pretreatment

Warning: It is *REQUIRED* that some form of pretreatment, such as a plunge pool, sump pit, filter strip, sedimentation basin, grass channel, or a combination of these practices be installed upstream of the infiltration practice.

It is *HIGHLY RECOMMENDED* that the following pretreatment sizing guidelines be followed:

- Before entering an infiltration practice, stormwater should first enter a pretreatment practice sized to treat a minimum volume of 25 percent of the V_{wq}.
- If the infiltration rate of the native soils exceeds 2 inches per hour a pretreatment practice capable of treating a minimum volume of 50 percent of the V_{wq} should be installed.
- If the infiltration rate of the native soils exceeds 5 inches per hour a pretreatment practice capable of treating a minimum volume of 100 percent of the V_{wq} should be installed.

It is *HIGHLY RECOMMENDED* that pretreatment practices be designed such that exit velocities from the pretreatment systems are non-erosive (less than 3 feet per second) and flows are evenly distributed across the width of the practice (e.g., by using a level spreader).

Depth

The depth of an infiltration practice is a function of the maximum drawdown time and the design infiltration rate.

Warning: The REQUIRED drawdown time for infiltration practices is 48 hours or less, and so the depth of the practice should be determined accordingly.

Warning:Groundwater Protection: It is *REQUIRED* that runoff from potential stormwater hotspots (PSHs) not be infiltrated unless adequate pretreatment has been provided. Infiltration of runoff from confirmed hotspot areas, industrial areas with exposed significant materials, or vehicle fueling and maintenance areas is *PROHIBITED*.

Materials specifications

Permeable pavement material specifications vary according to the specific pavement product selected. The following table describes general material specifications for the components installed beneath the permeable pavement. Note that the size of stone materials used in the reservoir and filter layers differ depending whether the system is pervious concrete, porous asphalt or permeable interlocking concrete pavement.

Summary of specifications for materials under the pavement surface. For more information, see the footnote ([1]). Reference or links to any specific commercial product, process, or service by trade name, trademark, service mark, manufacturer, or otherwise does not constitute or imply endorsement, recommendation, or favoring by the Minnesota Pollution Control Agency.

Link to this table

Material	Specification	Notes
Bedding/choker layer	• Pervious concrete: None • Porous asphalt: 1inch of AASHTO No. 57 stone • PICP: 2 inches of AASHTO No. 8 stone (MnDOT 3127FA-3)	Washed free of fines
Reservoir Layer	• Pervious concrete: AASHTO No. 57 stone or per hydraulic design • Porous asphalt:AASHTO No. 2, 3, or 5 stone • PICP: 4 inches of AASHTO No. 57 base and AASHTO No.2, 3 or 4 stone subbase	Stone layer thickness based on the pavement structural and hydraulic requirements. Stonewashed and free of fines. Recommended minimum void ratio = 0.4.
Underdrain (optional)	Use 4 to 6 inch diameter perforated PVC (AASHTO M-252) pipe or corrugated polyethylene pipe. Perforated pipe installed for the full length of the permeable pavement cell, and non-perforated pipe, as needed,connected to storm drainage system.	
Filter Layer (optional)	Sand filter layeris separated from base above and native soils with geotextile. Sand layer typically ASTM C33 gradation, 6 to 12 inches thick.	The Filter Layer is REQUIRED if using the permeable pavement system to meet permit requirements. The sand layer may require a choker layer on surface to provide transition to base layerstone.
Geotextile(optional)	Comply with AASHTO M-288 *Standard Specification for Geotextile Specification for Highway Applications*, drainage and separation applications, Class I or II. Porous asphalt industry recommends non-woven geotextile.	
Impermeable Liner	Use a minimum 30mil PVC liner covered by 12 ounce/square yard non-woven geotextile. EPDM and HDPE liner material is also acceptable.	
Observation Well	Use a perforated 4 to 6 inch vertical PVC pipe (AASHTO M-252) with a lockable cap, installedflush with the surface (or under pavers).	

[1]for additional information on materials referenced in this table (e.g. stone dimensions), see the following links:

- stone size 1, 2 (see Table 1)
- definitions of aggregates 1
- information on geotextiles 1, 2

- liners 1

A general comparison of different permeable pavements is provided in the following table. Designers should consult industry association and manufacturer's technical specifications for specific criteria and guidance.

This table shows summarizes specifications for permeable pavement.
Link to this table.

Material	Specification	Notes
Permeable Pavers	Surface open area: typically 5% to 15%; minimum thickness: 3 inches for vehicles; minimum compressive strength: 8,000 psi	Concrete pavers conform to ASTM C936 and clay pavers C1272. Reservoir layer required to support the structural load.
Pervious Concrete	• Void content: 15% to 35 % • Thickness: typically 5 to 8 inches	May not require a reservoir layer to support loads, but a layer is required for storage/infiltration. In no case should plain steel rebar or mesh be used in pervious concrete as this invites corrosion.
Porous Asphalt	• Void content: 16% to 20 % • Thickness: minimum 2.5 inch surface	Reservoir layer contributes to structural load support.

Other design considerations

There are additional design considerations for permeable pavement, including use of permeable pavement in karst terrain and winter considerations.

Karst terrain

A detailed geotechnical investigation may be required for any kind of stormwater design in karst terrain. Permeable pavements, as with other infiltration practices, are not recommended at sites with known karst features as they can cause the formation of sinkholes and can provide a direct link for stormwater to access groundwater without providing any treatment.

Winter considerations

Plowed snow piles should be located in adjacent grassy areas so that sediments and pollutants in snowmelt are partially treated before they reach all permeable pavements. Sand is not recommended for winter traction over permeable pavements. If sand is applied, it must be removed with vacuum cleaning in the spring. Traction can be accomplished on PICP using jointing stone materials, some of which will find its way into the joints by springtime. A significant winter advantage of permeable pavements is that they require less deicing materials than their impervious counterparts. Use of deicing material on permeable pavement is therefore not recommended.

Signage

Permeable pavements can be used as opportunities for public education with signs explaining how they work. Infiltration demonstrations also help show how the pavements work. Signs provide a reminder to maintenance crews of their presence and list maintenance do's and don'ts specific to the permeable pavement type.

Design checklists

Design checklists have not been developed for the Minnesota Stormwater Manual. We anticipate developing these in 2018. Below are links to checklists developed by other organizations.

- Iowa Stormwater Education Partnership, Permeable Paver Design Review Checklist
- Cartegraph, Permeable Pavement Design Review checklist

Construction specifications for permeable pavement

Green Infrastructure: Permeable pavement can be an important tool for retention and detention of stormwater runoff. Permeable pavement may provide additional benefits, including reducing the need for de-icing chemicals, and providing a durable and aesthetically pleasing surface.

Proper construction of permeable pavement is critical to its long term performance as a stormwater BMP. Improper or inadequate erosion and sediment control during construction and immediately following construction can cause immediate plugging of the pavement. The construction sequence is also critical to the long term success of the performance of the pavement and is described below. The materials and installation

techniques of the three different pavements are very specific and require special attention to detail. Failure to follow the recommendations will likely cause premature structural failure of the pavement or result is pavement without the desired infiltration capacity.

Essential erosion and sediment controls

See a video of permeable pavers being installed as part of the Blooming Alleys project.

All permeable pavement areas should be fully protected from sediment intrusion by silt fence or construction fencing, particularly if they are intended to infiltrate runoff. They should remain outside the limit of disturbance during construction to prevent soil compaction by heavy equipment. Permeable pavement areas should be clearly marked on all construction documents and grading plans. To prevent soil compaction, heavy vehicular traffic should be kept out of permeable pavement areas during and immediately after construction.

During construction, care should be taken to avoid tracking sediments onto any permeable pavement to avoid surface clogging. Any area of the site intended ultimately to be a permeable pavement area should generally not be used as the site of a temporary sediment basin. Where locating a sediment basin on an area intended for permeable pavement is unavoidable, the invert of the sediment basin must be a minimum of one foot above the final design elevation of the bottom of the aggregate reservoir course. All sediment deposits in the excavated area should be carefully removed prior to installing the subbase, base, and surface materials.

Permeable pavement construction sequence

The following is a typical construction sequence to properly install permeable pavement, which may be modified depending on the pavement type.

Step 1. Construction of the permeable pavement begins after the entire contributing drainage area has been stabilized. The proposed site should be checked for existing utilities prior to any excavation.

Caution: Do not install pervious concrete or porous asphalt in rain or snow, and do not install frozen aggregate materials under any of the surfaces

Step 2. Temporary erosion and sediment controls are needed during installation to divert stormwater away from the permeable pavement area until it is constructed and contributing drainage areas have been stabilized by a uniform perennial vegetative cover with a density of at least 70 percent over the entire pervious surface area, or other equivalent means. Special protection measures such as erosion control fabrics may be needed to protect vulnerable side slopes from erosion during and after the excavation process. The proposed permeable pavement area must be kept free from sediment during the entire construction process.

Caution: Construction materials contaminated by sediments must be removed and replaced with clean materials

Step 3. Where possible, excavation should work from the sides and outside the footprint of the permeable pavement area (to avoid soil compaction). Contractors can utilize a “cell” construction approach, whereby the proposed permeable pavement area is divided into 500 to 1000 square feet temporary cells with 10 to 15 feet wide earthen bridges between them so that the cells can be excavated from the side. Then the earthen bridges are removed. Excavated material should be placed away from the open excavation to maintain stability of the side walls.

Step 4. The native soils along the bottom of the permeable pavement system can be scarified or tilled to a depth of 3 to 4 inches and graded prior to the placement of the aggregate.

Step 5. Geotextile should be installed on the sides of the reservoir layer applications that do not use concrete curbs extending the full base depth. The design engineer may elect to use geotextile over the soil subgrade as well. Overlap of each sheet should follow recommendations in AASHTO M-288.

Step 6. Provide a minimum of 2 inches of aggregate around underdrain pipes. The underdrains should slope down towards the outlet at a grade of 0.5 percent or steeper. The up-gradient end of underdrains in the reservoir layer should be capped. Where an underdrain pipe is connected to a structure, there should be no perforations within at least one foot of the structure. Ensure that there are no perforations in clean-outs within at least one foot from the surface.

NOTE: Step 7 (below) previously specified minimum 8 inch lifts. A review of literature suggests this should be maximum lifts of 8 inches, with 4 to 6 inch lifts being preferred. See [8], [9], [10]

Step 7. Spread maximum 8 inch lifts (6 inch preferred) of the reservoir base/subbase or base stone. Moistening the aggregate during spreading will facilitate better compaction. Compact reservoir layers (layer with larger than No. 57 stone) with a 10 ton roller with two passes in static mode or until there is no visible movement of the aggregate. For No. 57 or similar sized stone layers, make two passes in vibratory mode and two passes in static mode or until there is no visible movement of the aggregate. Do not crush the aggregate with the roller. Corners and other areas where rollers cannot reach are compacted with a vibratory plate compactor capable of least 13,500 pound force (lbf) and equipped with a compaction indicator. PICP bases require a 4 inch base layer and this is compacted separately from the subbase layer with two passes in vibratory then two in static mode.

Step 8. Install the desired depth of the bedding or choker layer, depending on the type of pavement, as follows.

- Pervious Concrete: No bedding/choker layer is used.
- Porous Asphalt: The choker layer for porous asphalt pavement consists of 1 inch of washed No. 57 stone.
- PICP: The bedding layer for open-jointed pavement blocks should consist of 2 inches of washed No.8 stone. This layer is compacted after pavers are placed on it and their joints are filled with aggregate.

Step 9. Paving materials should be installed according to manufacturer or industry specifications for the particular type of pavement. Installation highlights are provided below. After the installation is complete, the permeable pavement surface should be tested for acceptance using a minimum infiltration rate of 100 inch/hr using ASTM C1701 *Standard Test Method for Infiltration Rate of In Place Pervious Concrete*. This test method can be used on porous asphalt and PICP.

Porous asphalt installation

The following has been excerpted from the Minnesota Asphalt Pavement Association (MAPA 2012) and from the National Asphalt Pavement Association (Hansen 2008). These documents should be reviewed for detailed specifications.

- Use PG 58-28 or PG 64-22 asphalt binder.
- Install porous asphalt pavement at according to temperatures recommended in the aforementioned references with a minimum air temperature of 50oF to ensure that the surface does not stiffen before compaction.
- Complete compaction of the surface course when the surface is cool enough to resist a 10-ton roller. One or two passes of the roller are required for proper compaction. More rolling could cause a reduction in the porosity of the pavement.
- The mixing plant must provide certification of the aggregate mix, abrasion loss factor, and asphalt content in the mix.
- Transport the mix to the site in a clean truck with smooth dump beds sprayed with a non-petroleum release agent. The mix should be covered during transportation to control cooling.

Pervious concrete installation

The basic installation sequence for pervious concrete is outlined by the American Concrete Institute in ACI Specification 522.1 (ACI 2010) and can be purchased from the American Concrete Institute. Guide specifications for Minnesota applications should be obtained from the Aggregate and Ready Mix Association of Minnesota. Concrete installers should successfully complete a recognized pervious concrete installers training program, the Pervious Concrete Contractor Certification Program offered by the National Ready Mix Concrete Association. The basic installation procedure follows:

- Water the underlying aggregate (reservoir layer) before the concrete is placed, so that the aggregate does not draw moisture from the freshly laid pervious concrete.
- After the concrete is placed, approximately 3/8 to 1/2 inch is struck off, using a vibratory screed. This is to allow for compaction of the concrete pavement.
- Compact the pavement with a steel pipe roller. Care should be taken so that over-compaction does not occur.
- Cut joints for the concrete to a depth of ¼ inch.
- Curing: Cover the pavement with plastic sheeting within 20 minutes of the strike-off, and keep it covered for at least seven days. Do not allow traffic on the pavement during this time period.

Installation of interlocking pavers

The basic installation process is described in greater detail by Smith (Smith 2011). Permeable paver job foremen should successfully complete the PICP Installer Technician Course training program offered by the Interlocking Concrete Pavement Institute (ICPI). The ICPI provides a variety of technical courses.

The following installation method also applies to clay paving units. Contact manufacturers of composite units for installation specifications. Guide construction specifications are available from the Interlocking Concrete Pavement Institute.

- Moisten, place and level the AASHTO No. 2 stone subbase and compact it in minimum 12 inch thick lifts with four passes of a 10-ton steel drum static roller until there is no visible movement. The first two passes are in vibratory mode with the final two passes in static mode. The filter aggregate should be moist to facilitate movement into the reservoir course.
- Place edge restraints before the base layer, bedding and pavers are installed. Permeable interlocking pavement systems require edge restraints to prevent vehicle tires from moving the pavers. Edge restraints may be standard concrete curbs or curb and gutters.
- Moisten, place and level the AASHTO No. 57 base stone in a single lift (4 inches thick). Compact it into the reservoir course beneath with at least four (4) passes of a 10-ton steel drum static roller until there is no visible movement. The first two passes are in vibratory mode, with the final two passes in static mode.
- Place and screed the bedding course material (typically AASHTO No. 8 stone (MnDOT 3127-FA-3), 2 inches thick).
- Pavers may be placed by hand or with mechanical installation equipment.
- Fill gaps at the edge of the paved areas with cut pavers or edge units. When cut pavers are needed, cut the pavers with a paver splitter or masonry saw. Cut pavers no smaller than one-third (1/3) of the full unit size if subject to tires.
- Fill the joints and openings with stone. Joint openings must be filled with AASHTO No. 8 (MnDOT 3127-FA-3), 89 or 9 (MnDOT 3127 FA-2)stone per the paver manufacturer’s recommendation. Sweep and remove excess stones from the paver surface.
- Compact and seat the pavers into the bedding course with a minimum low-amplitude 5,000 lbf, 75- to 95 Hz plate compactor. Do not compact within 6 feet of the unrestrained edges of the pavers.
- Thoroughly sweep the surface after construction to remove all excess aggregate.
- Inspect the area for settlement. Any paving units that settle must be reset and inspected.
- The contractor should return to the site within 6 months to top up the paver joints with stones.

Construction inspection

Inspections before, during and after construction are needed to ensure that permeable pavement is built in accordance with these specifications. Use a detailed inspection checklist that requires sign-offs by qualified individuals at critical stages of construction and to ensure that the contractor’s interpretation of the plan is consistent with the designer’s intent. The following checklist provides an example.

Pre-construction meeting

- Walk through site with builder/contractor/subcontractor to review erosion and sediment control plan/stormwater pollution prevention plan (SWPPP)
- Determine when permeable pavement is built in project construction sequence; before or after building construction and determine measures for protection and surface cleaning
- Aggregate material locations identified (hard surface or on geotextile)

Sediment management

- Access routes for delivery and construction vehicles identified
- Vehicle tire/track washing station location/maintenance (if specified in the erosion and sediment control plan (SWPPP))
- Ensure that the contributing drainage areas are stabilized and are not eroding

Excavation

- Utilities should be located and marked by local service provider
- The excavated area should be marked with paint and/or stakes
- The excavation size and location should conform to the plan
- Excavation hole as sediment trap: The hole cleaned should be cleaned immediately before subbase stone placement and runoff sources with sediment diverted away from the pavement or all runoff diverted away from the excavated area.
- Temporary soil stockpiles should be protected from run-on, run-off from adjacent areas and from erosion by wind.
- Ensure linear sediment barriers (if used) are properly installed, free of accumulated litter, and built up sediment less than 1/3 the height of the barrier.
- No runoff should enter the pavement until soils are stabilized in the area draining to the pavement
- Foundation walls should be waterproofed
- Soil subgrade: rocks and roots removed, voids should be refilled with base aggregate
- Soil should be compacted to specifications (if required) and field tested with density measurements per specifications
- No groundwater seepage or standing water. If groundwater seepage is present, dewatering and possibly a dewatering permit may be required.

Geotextiles

- Must meet the design specifications
- Sides of excavation should be covered with geotextile prior to placing aggregate base/subbase
- Placement and down slope overlap (minimum of 2 feet) should conform to specifications and drawings
- No tears or holes should be present
- No wrinkles should be present and the fabric should be pulled taught and staked

Impermeable liners (if specified; see here)

- Must meet the specifications
- Placement, field welding, and seals at pipe penetrations should be completed per the design specifications

Drain pipes/observation wells

- Size, perforations, locations, slope, and outfalls must meet specifications and drawings
- Verify the elevation of overflow pipes
- Underdrains should be capped at upslope ends

Aggregates

- Test results should conform to specifications
- Aggregates should be spread (not dumped) with a front-end loader to avoid aggregate segregation
- Storage on hard surface or on geotextile to keep sediment-free
- Thickness, placement, compaction and surface tolerances should meet specifications and drawings

Once the final construction inspection has been completed, log the GPS coordinates for each facility and submit them for entry into the local BMP maintenance tracking database.

Construction inspection checklists

Construction inspection checklists have not been developed for the Minnesota Stormwater Manual. We anticipate developing these in 2018. Below are links to checklists developed by other organizations.

- Fairfax County, 3rd Party Construction Inspection Checklist and Certification: Permeable Pavement
- Prince George's County, Permeable Pavement Construction Inspection Checklist

Minnesota Department of Transportation example construction protocols

Preliminary analysis and selection

Recommended number of soil borings, pits or permeameter tests for bioretention design. Designers select one of these methods.
Link to this table

Surface area of stormwater control measure (BMP)(ft^2)	Borings	Pits	Permeameter tests

Surface area of stormwater control measure (BMP)(ft)	Borings	Pits	Permeameter tests
< 1000	1	1	5
1000 to 5000	2	2	10
5000 to 10000	3	3	15
>10000	4[1]	4[1]	20[2]

[1]an additional soil boring or pit should be completed for each additional 2,500 ft^2 above 12,500 ft^2

[2]an additional five permeameter tests should be completed for each additional 5,000 ft^2 above 15,000 ft^2

Field verification testing prior to pond construction

- Soil hydraulic group represent what is stated in SWPPP (Stormwater Pollution Prevention Plan)
- Seasonally high water table not discovered within 3 feet of the excavated pond base within a test pit
- Commonly will test bottom of proposed pond for soil compaction (subsequent subsoil ripping) prior to media placement
- Commonly will test bottom of proposed pond for insitu infiltration rate by test pit or water filled barrel placed on pond base surface

Filter media and material testing

- Existing soil (option 1 below) or Washed sand (option 2 below), and compost certification
- Washed course aggregate choker certification
- Other treatment material certification of iron filings, activated charcoal, pH buffers, minerals, etc.
- Geotextile separation fabric certification
- Drain-tile certification (if filtration is specified)
- Seed source certification
- Barrel test verification of infiltration rate using 2.5 feet of imported 3877 Type G media

Field verification testing/inspection/verification during construction

- Water drains away in 48 hours
- Infiltration drainage rate does not exceed 8.3 inches per hour
- No tracking/equipment in pond bottom
- No sediment deposits from ongoing construction activity, media perimeter controls kept functional

- Forebay is trapping settleable solids, floating materials, and oil/grease
- Area staked off

Notice of Termination (NOT) verification

- **Option 1. Amending existing HSG soils with compost or other treatment material.** Test the infiltration rate of each infiltration basin using a double ring infiltrometer prior to completion of the basin. Conduct the test at the finished grade of the basin bottom, prior to blending the compost with the in-situ soils or sand. Ensure infiltration rates meet or exceed greater of two times the designed infiltration rate or 2 inches per hour. Conduct a minimum of five tests per representative acre of basin area and a minimum of five tests per basin. Conduct double ring infiltrometer tests in accordance with ASTM standards. Thoroughly wet test areas prior to conducting infiltrometer tests.
- **Option 2. Importing 3877 Type G Filter Topsoil Borrow (may be amended with other treatment material)**. Ensure infiltration rates meet or exceed greater of two times the designed infiltration rate or 2 inches per hour, or rate specified in the plan. Conduct a minimum of five tests per representative acre of basin area and a minimum of five tests per basin. Conduct double ring infiltrometer tests in accordance with ASTM standards. Thoroughly wet test areas prior to conducting infiltrometer tests. Amend soils with additional washed sand if rates less than specified in the contract, or compost if rates exceed 8.3 inches per hour.

The permanent stormwater management system must meet all requirements in sections 15, 16, and 17 of the CSW permit and must operate as designed. Temporary or permanent sedimentation basins that are to be used as permanent water quality management basins have been cleaned of any accumulated sediment. All sediment has been removed from conveyance systems and ditches are stabilized with permanent cover.

Related articles

- Overview for permeable pavement
- Types of permeable pavement
- Design criteria for permeable pavement
- Construction specifications for permeable pavement
- Assessing the performance of permeable pavement
- Operation and maintenance of permeable pavement
- Calculating credits for permeable pavement
- Case studies for permeable pavement
- Green Infrastructure benefits of permeable pavement
- Summary of permit requirements for infiltration
- Permeable pavement photo gallery
- Additional considerations for permeable pavement
- Links for permeable pavement
- References for permeable pavement
- Fact sheets for permeable pavement

- Requirements, recommendations and information for using permeable pavement BMPs in the MIDS calculator

Permeable pavement main page </noinclude>

Operation and maintenance of permeable pavement

Green Infrastructure: Permeable pavement can be an important tool for retention and detention of stormwater runoff. Permeable pavement may provide additional benefits, including reducing the need for de-icing chemicals, and providing a durable and aesthetically pleasing surface.

Maintenance and maintenance agreements

In addition to the design items previously mentioned, some key actions help ensure the long-term performance of permeable pavement during its operation life. The most frequently cited maintenance problem is surface clogging caused by organic matter and sediment, which can be reduced by the following measures:

- Periodic Vacuuming – The pavement surface is the first line of defense in trapping and eliminating sediment that may otherwise enter the stone base and soil subgrade. The rate of sediment deposition should be monitored and vacuuming done at least two times per year. A typical vacuum cleaning schedule may include the end of winter (April) and after autumn leaf-fall (November). Maintenance records should be maintained by the owner. The vacuuming frequency should be adjusted according to the intensity of use and deposition rate on the permeable pavement surface. At least one pass should occur at the end of winter. Regenerative air vacuum sweepers are the suggested means for regular surface cleaning. For neglected surfaces (i.e., those with no surface cleaning over several years) true vacuum sweepers have the most efficient removal of debris and fine particulates when compared with regenerative air or mechanical sweepers. However, areas on steep slopes or near curbs may limit vacuum sweeper performance (Brown 2013). If a true vacuum sweeper is used on PICP the removed aggregate in the joints should be replaced with the same material.
- Ongoing – Minimizing salt use or sand for de-icing and traction in the winter, keeping the landscaping areas well maintained and preventing soil from being washed onto the pavement helps increase its life. Less salt will be needed. However, such water should not be directed to irrigation uses.
- Maintenance Agreements - Maintenance agreements should note which conventional parking lot maintenance tasks must be avoided (e.g., sanding, re-sealing, re-surfacing, power-washing). Signs should be posted on parking lots to indicate their stormwater function and special maintenance requirements. When permeable pavements are installed on private residential or commercial property, owners must understand routine maintenance requirements. These requirements can be enforced via a deed restriction, drainage easement, maintenance agreement, performance

The Chesapeake Stormwater Network has developed two videos that illustrate inspection and maintenance of LID BMP practices, including permeable pavement. **NOTE: These videos provide useful tips but should not be used for compliance with**

bond, letter of credit or other mechanism enforceable by the local authority to help ensure that the permeable pavement is maintained and continues functioning. The local authority should use this MIDS guideline to establish measurable performance criteria for enforcing maintenance procedures. The mechanism should, if possible, grant authority for local agencies to enter the property for inspection or corrective action.

Minnesota permits.

Maintenance inspection and maintenance checklists

Inspection and maintenance checklists have not been developed for the Minnesota Stormwater manual. We anticipate developing these in 2018. Below are several links to checklists developed by other organizations.

- Chagrin River Watershed Partners Permeable Pavement Inspection and Maintenance Checklist
- City of Franklin, Tennessee Stormwater Division Permeable Pavement Inspection and Maintenance Checklist
- Franklin Township, New Jersey, Permeable Pavement Maintenance Inspection Checklist

Links to additional information

- File:Pervious Pavement Maintenance Guide public use.pdf. (Source:Ramsey-Washington Watershed District)
- File:Grass Pavers Maintenance Guide public use.pdf. (Source:Ramsey-Washington Watershed District)
- Maintaining Permeable Pavements. North Carolina Cooperative Extension.
- Pervious Concrete Pavement Maintenance and Operations Guide. National Ready Mixed Concrete Association.

Assessing the performance of permeable pavement

Green Infrastructure: Permeable pavement can be an important tool for retention and detention of stormwater runoff. Permeable pavement may provide additional benefits, including reducing the need for de-icing chemicals, and providing a durable and aesthetically pleasing surface.

Maintenance of permeable pavement includes a review of its condition and performance. A spring maintenance inspection is recommended and cleanup conducted as needed. The following are recommended annual maintenance inspection points for permeable pavements:

- The drawdown rate should be measured at the observation well for three (3) days following a storm event in excess of 1/2 inch in depth. If standing water is still observed in the well after two days, this is a clear sign the system is not performing as desired and subgrade soil clogging is a problem.

- Inspect the surface for evidence of sediment deposition, organic debris, water staining, or ponding that may indicate surface clogging. If any signs of clogging are noted, schedule a vacuum sweeper to remove deposited material. Then test sections using ASTM C1701 to ensure that the surface attains an infiltration rate of at least 10 inches per hour.
- Check inlets, pretreatment cells and any flow diversion structures for sediment buildup and structural damage. Remove the sediment.
- Inspect any contributing drainage area for any controllable sources of sediment or erosion
- Inspect the condition of the observation well and make sure it is capped.
- Inspect the structural integrity of the pavement surface, looking for signs of surface deterioration, such as slumping, cracking, spalling, or broken pavers. Replacement to rectify a damaged surface or one removed for access to utility repairs should be done per industry recommendations. After base compaction, small areas of pervious concrete and porous asphalt can be replaced with conventional (impervious) asphalt or concrete up to 10 percent of the total permeable pavement area. For PICP, paving units are removed for reinstatement later. The remaining undisturbed pavers at the perimeter of the opening are typically held in place with temporary wood or metal braces. Once the base is replaced and compacted, new bedding material and pavers are reinstated and compacted over the base.

An online manual for assessing BMP treatment performance was developed in 2010 by Andrew Erickson, Peter Weiss, and John Gulliver from the University of Minnesota and St. Anthony Falls Hydraulic Laboratory. The manual advises on a four-level process to assess the performance of a Best Management Practice.

- Level 1: Visual Inspection. This includes assessments for infiltration practices and for filtration practices. The website includes links to a downloadable checklist.
- Level 2: Capacity Testing. Level 2 testing can be applied to both infiltration and filtration practices.
- Level 3: Synthetic Runoff Testing for infiltration and filtration practices. Synthetic runoff test results can be used to develop an accurate characterization of pollutant retention or removal, but can be limited by the need for an available water volume and discharge.
- Level 4: Monitoring for infiltration or filtration practices

Level 1 activities do not produce numerical performance data that could be used to obtain a stormwater management credit. BMP owners and operators who are interested in using data obtained from Levels 2 and 3 should consult with the MPCA or other regulatory agency to determine if the results are appropriate for credit calculations. Level 4, Monitoring, is the method most frequently used for assessment of the performance of a BMP.

Use these links to obtain detailed information on the following topics related to BMP performance monitoring:

- Developing an Assessment Program
- Water Budget Measurement
- Sampling Methods
- Analysis of Water and Soils
- Data Analysis for Monitoring

Additional information on designing a monitoring network and performing field monitoring are found at this link.

Calculating credits for permeable pavement

Warning: Models are often selected to calculate credits. The model selected depends on your objectives. For compliance with the Construction Stormwater permit, the model must be based on the assumption that an instantaneous volume is captured by the BMP.

Green Infrastructure: Permeable pavement can be an important tool for retention and detention of stormwater runoff. Permeable pavement may provide additional benefits, including reducing the need for de-icing chemicals, and providing a durable and aesthetically pleasing surface.

Recommended pollutant removal efficiencies, in percent, for permeable pavement with an underdrain. Sources. NOTE: removal efficiencies are 100 percent of captured water for systems with no underdrain.

TSS=total suspended solids; TP=total phosphorus; PP=particulate phosphorus; DP=dissolved phosphorus; TN=total nitrogen

TSS	TP	PP	DP	TN	Metals	Bacteria	Hydrocarbons
74	45	82	0	insufficient data	insufficient data	insufficient data	insufficient data

Credit refers to the quantity of stormwater or pollutant reduction achieved either by an individual Best Management Practice (BMP) or cumulatively with multiple BMPs. Stormwater credits are a tool for local stormwater authorities who are interested in

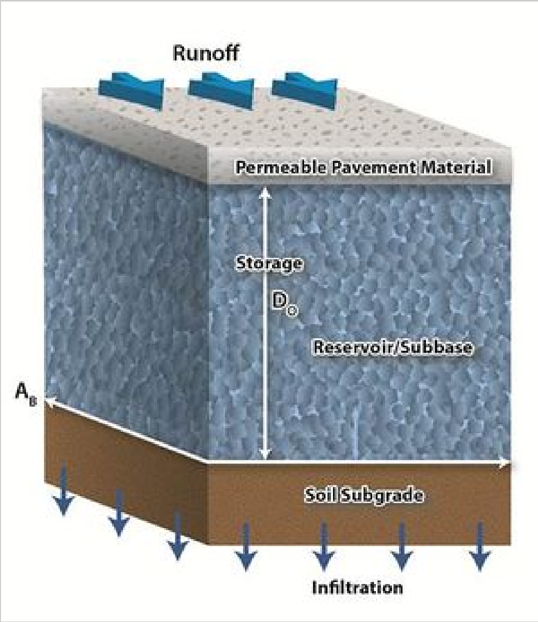
- providing incentives to site developers to encourage the preservation of natural areas and the reduction of the volume of stormwater runoff being conveyed to a best management practice (BMP);
- complying with permit requirements, including antidegradation (see [11]; [12]);
- meeting the MIDS performance goal; or
- meeting or complying with water quality objectives, including Total Maximum Daily Load (TMDL) Wasteload Allocations (WLAs).

This page provides a discussion of how permeable pavement practices can achieve stormwater credits. Permeable pavement systems with and without underdrains are both discussed, with separate sections for each type of system as appropriate.

Overview

Permeable pavements are a stormwater quality practice that allows runoff to pass through surface voids into an underlying stone reservoir/subbase for temporary storage before being discharged to an underdrain and/or underlying soil via infiltration. The most commonly used types of permeable pavement are pervious concrete, porous asphalt, and permeable interlocking concrete pavers.

Pollutant removal mechanisms



Schematic of a permeable pavement system with no underdrain. Water infiltrating through the pavement is stored in the reservoir/subbase and infiltrates into the underlying soil subgrade within a specified drawdown time, usually 48 hours.

Permeable pavement systems with no underdrains provide stormwater pollutant removal by reducing the volume of runoff from a site and the pollutant mass associated with that volume when infiltration is allowed (Water Environment Federation, 2012). In systems with underdrains most of the water is captured by the underdrain after passing through the subbase. If the underdrain is raised above the underlying soil subgrade, water stored in the reservoir/subbase below the underdrain will infiltrate into the underlying soil. If the underdrain is at the bottom of the reservoir/subbase, a small amount of infiltration may occur. Thus, pollutant removal in a permeable pavement system with an underdrain occurs through filtering of water captured by the underdrain and infiltration for water infiltrating into the underlying soil subgrade.

Location in the treatment train

Stormwater Treatment Trains are comprised of multiple Best Management Practices that work together to minimize the volume of stormwater runoff, remove pollutants, and reduce the rate of stormwater runoff being discharged to Minnesota wetlands, lakes and streams. Permeable pavements are installed near the start of the treatment train as a method that directs the stormwater runoff to a subgrade storage area in order to minimize the volume and pollutant mass of stormwater runoff .

Methodology for calculating credits

This section describes the basic concepts and equations used to calculate credits for volume, Total Suspended Solids (TSS) and Total Phosphorus (TP). Specific methods for calculating credits are discussed later in this article. Permeable pavement is also effective at reducing concentrations of other pollutants including nitrogen, metals, bacteria, and hydrocarbons. This article does not provide information on calculating credits for pollutants other than TSS and TP, but references are provided that may be useful for calculating credits for other pollutants.

Assumptions and approach

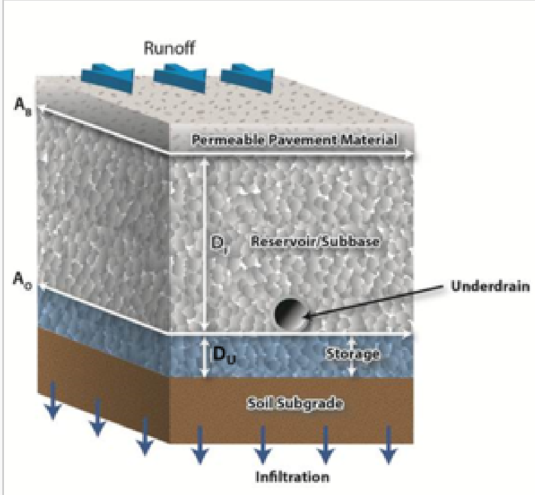
In developing the credit calculations, it is assumed the permeable pavement practice is properly designed, constructed, and maintained in accordance with the Minnesota Stormwater Manual. If any of these assumptions is not valid, the BMP may not qualify for credits or credits should be reduced based on reduced ability of the BMP to achieve volume or pollutant reductions. For guidance on design, construction, and maintenance, see the appropriate article within the permeable pavement section of the Manual.

Warning: Pre-treatment is required for all filtration and infiltration practices

In the following discussion, the water quality volume (V_{WQ}) is assumed to be delivered instantaneously to the BMP. The V_{WQ} is stored within the reservoir/subbase below the bottom of the pavement and above the soil subgrade. The V_{WQ} can vary depending on the stormwater management objective(s). For construction stormwater, the water quality volume is 1 inch times the new impervious surface area. For MIDS, the V_{WQ} is 1.1 inches times the impervious surface area. In reality, some water will infiltrate through the bottom and sidewalls of the BMP as a rain event proceeds. The instantaneous method therefore may underestimate actual volume and pollutant losses.

The approach in the following sections is based on the following general design considerations.

- Credit calculations presented in this article are for both event and annual volume and pollutant load removals.
- Stormwater volume credit for permeable pavements equates to the volume of runoff that is fully contained within the stone reservoir/subbase that will ultimately be infiltrated into the soil subgrade.
- TSS and TP credits for permeable pavements are achieved for the volume of runoff that is filtered and captured by an underdrain and the volume of water that is ultimately infiltrated.



Schematic of a permeable pavement system with an underdrain. Water infiltrating through the pavement is either captured by the underdrain or stored below the underdrain in the reservoir/subbase, where it infiltrates into the underlying soil subgrade within a specified drawdown time, usually 48 hours.

Volume credit calculations - no underdrain

Volume credits are calculated based on the capacity of the BMP and its ability to permanently remove stormwater runoff via infiltration into the underlying soil from the existing stormwater collection system. These credits are assumed to be instantaneous values entirely based on the capacity of the BMP to capture, store, and transmit water in any storm event.

Volume credits for a permeable pavement system are based on the porosity of the subbase and system dimensions, specifically the depth of the reservoir/ subbase, the area of permeable pavement, and the bottom surface area. The volume credit (V_{inf_b}) for infiltration through the bottom of the BMP into the underlying soil, in cubic feet, is given by

$V_{inf_b} = D_o\ n\ (A_O + A_B)\ / 2$

where

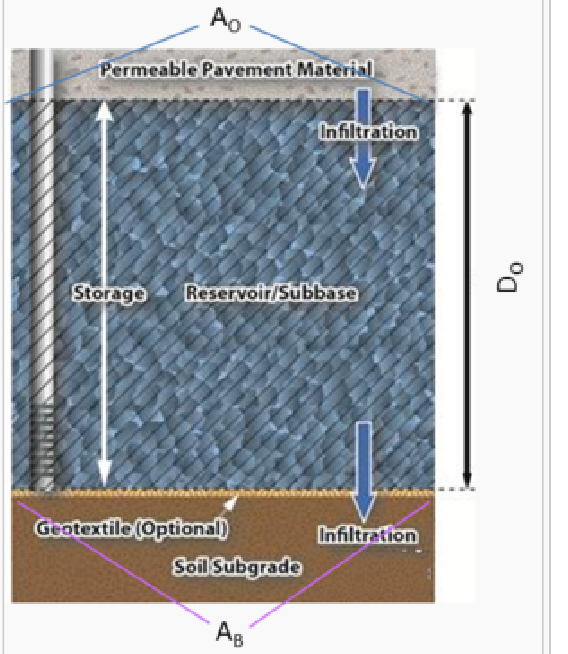
A_O is the overflow surface area of the permeable pavement system, in square feet;

A_B is the depth at the bottom of the permeable pavement system, in square feet;
D_O is the depth of the reservoir/subbase layer (engineered media), equal to the distance from the bottom of the permeable pavement material to the underlying soil subgrade, in feet; and
n is the porosity of the reservoir/subbase, in cubic feet per cubic foot.

The subbase depth should be limited to the drawdown time. The construction stormwater general permit requires a maximum 48 hour drawdown time (24 hours is recommended for discharges to trout streams). For example, using a Hydrologic Soil Group B (SM) soil with an infiltration rate of 0.45 inches per hour, the maximum depth is 1.8 feet.

Note that that entire porosity of the subbase layer is used to calculate the volume credit. This slightly overestimates the actual volume infiltrated since some water is held by the media after the runoff infiltrates. The water content after gravity drainage, called field capacity, is less than 5 percent of total porosity for a permeable pavement system.

The annual volume captured and infiltrated by the BMP can be determined with appropriate modeling tools, including the MIDS calculator. Example values are shown below for a scenario using the MIDS calculator. For example, a permeable pavement system designed to capture 1 inch of runoff from impervious surfaces will capture 89 percent of annual runoff from a site with B (SM) soils.



Schematic showing terminology for calculating volume credits for permeable pavement. A_O is the area at the bottom of the pavement, A_B the area at the reservoir/soil subgrade interface, and D_O the depth or thickness of the reservoir.

Annual volume, expressed as a percent of annual runoff, treated by a BMP as a function of soil and water quality volume. See footnote[1] for how these were determined.

Link to this table

Soil	Water quality volume (V_{WQ}) (inches)				
	0.5	0.75	1.00	1.25	1.50
A (GW)	84	92	96	98	99
A (SP)	75	86	92	95	97
B (SM)	68	81	89	93	95
B (MH)	65	78	86	91	94
C	63	76	85	90	93

[1]Values were determined using the MIDS calculator. BMPs were sized to exactly meet the water quality volume for a 2 acre site with 1 acre of impervious, 1 acre of forested land, and annual rainfall of 31.9 inches.

Volume calculations - underdrain

The volume credit (V) for permeable pavement systems with underdrains, in cubic feet, is given by

$V = V_{inf_b} + V_U$

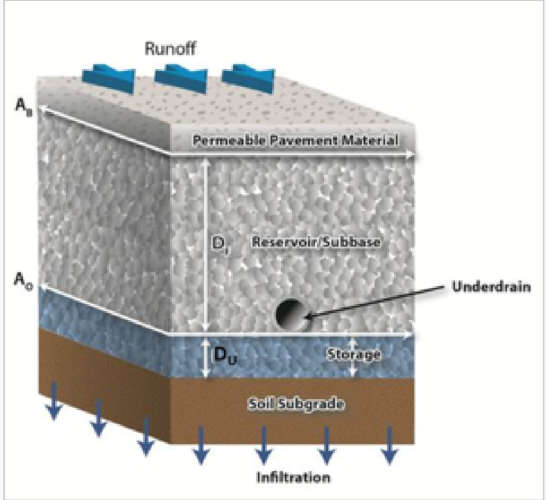
The infiltrating volume (V_{inf_b}), in cubic feet, is given by

$V_{inf_b} = A_B DDT I_R / 12$

where

A_B is the surface area at the bottom of the underdrain, in square feet;
DDT is the drawdown time for water stored below the underdrain, in hours; and
I_R is the design infiltration rate of underlying soil, in inches per hour.

Information: The MIDS calculator assigns a default value of 0.06 inches per hour, equivalent to a D soil, to I_R. This is based on the assumption that most water will drain to the underdrain, but that some loss to underlying soil will occur. A conservative approach assuming a D soil was thus chosen.



Schematic of a permeable pavement system with an underdrain. Water infiltrating through the pavement is either captured by the underdrain or stored below the underdrain in the reservoir/subbase, where it infiltrates into the underlying soil subgrade within a specified drawdown time, usually 48 hours.

The construction stormwater general permit requires a maximum 48 hour drawdown time (24 hours is recommended for discharges to trout streams). Note the MIDS calculator does not provide a volume credit for a permeable pavement system with an underdrain at the bottom.

If the underdrain is raised above the bottom of the BMP (i.e. above the interface between the reservoir/subbase and underlying soil subgrade), water stored below the underdrain will infiltrate. The infiltrating volume (V_U), in cubic feet, is given by

$V_U = D_u\ n\ (A_U + A_B)\ / 2$

where

D_u is the depth of the reservoir layer below the underdrain, in feet;
A_B is the surface area at the bottom of the underdrain, in square feet;
A_U is the surface area at the bottom of the reservoir layer/subbase, in square feet; and
n is the porosity of the reservoir/subbase layer, in cubic feet per cubic foot.

The depth below the underdrain should be limited to the drawdown time. The construction stormwater general permit requires a maximum 48 hour drawdown time (24 hours is recommended for discharges to trout streams). For example, using a Hydrologic Soil Group C soil with an infiltration rate of 0.2 inches per hour, the maximum depth below the underdrain is 0.8 feet.

Total Suspended Solids (TSS)

The TSS credits available for installation of permeable pavement depend on the design of the storage volume below the pavement and whether the runoff is filtered (through an underdrain), infiltrated, or both. Designs that filter runoff with an underdrain at the bottom of the storage layer are less effective in removing pollutants than infiltration designs. Runoff is filtered while flowing through the permeable pavement and the storage layer and out the underdrain. TSS removal credit of 100 percent is assumed for the infiltrated water. The recommended removal rate for filtered water is 74 percent, based on review of literature.

Removal of TSS by permeable pavement (M_{TSS}), in pounds per event or pounds per year, is given by

$M_{TSS} = M_{TSS_I}\ + M_{TSS_F}$

where

M_{TSS_I} = mass of TSS removed by infiltration (pounds per event or pounds per year); and
M_{TSS_F} = mass of TSS removed by filtration (pounds per event or pounds per year).

The annual TSS credit (M_{TSS_I}) for infiltrated runoff is given by

$M_{TSS_I} = 2.72\ V_{_{Annual}}\ F_I\ EMC_{_{TSS}}$

where

V_{Annual} is the annual volume treated by the BMP, in acre-feet;
F_I is the fraction of the total annual volume treated by the BMP that is infiltrated;
EMC_{TSS} = event mean concentration of TSS in the runoff, in mg/L; and
Factor of 2.72 used for conversion to pounds.

In a permeable pavement system with an underdrain, some of the water captured by the BMP will enter the underdrain while some will infiltrate below the underdrain. The amount infiltrating depends on several factors, including whether the underdrain is raised above the soil subgrade, the

infiltration rate of the underlying soil, and size and spacing of the underdrains. Pollutants in water that enters the underdrain are filtered. The Annual TSS credit for filtered runoff (M_{TSS_F}) is given by

$M_{TSS_F} = 2.72\ R_{_{TSS}}\ V_{_{Annual}}\ (F_F)\ EMC_{_{TSS}}$

where

> F_F is the fraction of the total volume treated by the BMP that is filtered; and
> R_{TSS} is the pollutant removal fraction for filtered water. A value of 0.74 is recommended.

If the permeable pavement is not the upstream most BMP in the treatment train, EMC_{TSS} should be dependent on the M_{TSS} effluent (mg/L) from the next upstream tributary BMP.

The annual volume treated by the BMP can be determined with appropriate modeling tools, including the MIDS calculator. Example values are shown below for a scenario using the MIDS calculator. For example, a permeable pavement system designed to capture 1 inch of runoff from impervious surfaces will capture 89 percent of annual runoff from a site with B (SM) soils. If an underdrain is in the system, this volume will have to be divided into the portion that infiltrates and the portion that is captured by the underdrain. The MIDS calculator can be used to determine these values.

Annual volume, expressed as a percent of annual runoff, treated by a BMP as a function of soil and water quality volume. See footnote[1] for how these were determined.
Link to this table

	Water quality volume (V_{WQ}) (inches)				
Soil	**0.5**	**0.75**	**1.00**	**1.25**	**1.50**
A (GW)	84	92	96	98	99
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B (SM)	68	81	89	93	95
B (MH)	65	78	86	91	94
C	63	76	85	90	93

[1]Values were determined using the MIDS calculator. BMPs were sized to exactly meet the water quality volume for a 2 acre site with 1 acre of impervious, 1 acre of forested land, and annual rainfall of 31.9 inches.

The event (storm) based TSS credit (M_{TSS_I}) for infiltrated runoff is given by

$M_{TSS_I} = 2.72\ V_I\ EMC_{_{TSS}}\ / 43,560$

where

V_I is the event-based volume infiltrated by the BMP, in cubic feet, and
a factor of 43,560 is used for conversion of volume from cubic feet to acre-ft.

The storm event based TSS credit (M_{TSS-F}) for filtered runoff is given by

$M_{TSS_F} = R_{_{TSS}}\ 2.72\ V_F\ EMC_{_{TSS}}\ / 43560$

where

V_F is the event-based volume filtrated by the BMP, in cubic feet.

Total phosphorus (TP) credit calculations

Similar to TSS, TP reduction credits correspond directly with volume reduction through infiltration and filtration of captured stormwater. The water quality credits available for a permeable pavement system depend on the design of the storage volume below the pavement and whether or not the runoff is filtered (through underdrain) or infiltrated. TP credit is divided into particulate phosphorus (PP) and dissolved phosphorus (DP) removal, respectively making up 55 percent and 45 percent of the total TP credit. Because the volume of infiltrated water (calculated above) is completely removed from the existing system, 100 percent TP credit is assumed for all infiltrated stormwater. Filtered stormwater only receives credit for PP credit, and no credit is given for DP. This approach is consistent with the approach used in the MIDS calculator.

Removal of TP by permeable pavement is given by

$M_{TP} = M_{TP_I}\ + M_{TP_F}$

where

M_{TP} is the annual or event TP removal (lb/yr or lb/event);
M_{TP_I} is the annual or event TP removal from infiltrated runoff (lb/yr or lb/event); and
M_{TP_F} is the annual or event TP removal from filtered water (lb/year or lb/event).

The total annual TP removal for infiltrated runoff is given by

$M_{TP_I} = 2.72\ V_{annual}\ F_I\ EMC_{_{TP}}$

where

V_{annual} is the annual volume treated by the BMP, in acre-feet,
F_I is the fraction of the total annual volume treated by the BMP that is infiltrated,
EMC_{TP} = event mean concentration of TP in the runoff, in mg/L, and
a factor of 2.72 used for conversion to pounds.

In a permeable pavement system with an underdrain, some of the water captured by the BMP will enter the underdrain while some will infiltrate below the underdrain. The amount infiltrating depends on several factors, including whether the underdrain is raised above the soil subgrade, the infiltration rate of the underlying soil, and size and spacing of the underdrains. Pollutants in water that enters the underdrain are filtered. The Annual TP credit for filtered runoff (M_{TP_F}) is given by

$M_{TP_F} = 2.72\ R_{_{TP}}\ V_{_{Annual}}\ F_F\ EMC_{_{TP}}$

where

F_F is the fraction of the total volume treated by the BMP that is filtered; and
R_{TP} is the pollutant removal fraction for filtered water.

The pollutant removal fraction applies only to particulate phosphorus (PP), which is assumed to be 55 percent of total phosphorus (TP). The recommended removal efficiency for PP is 82 percent. Thus, the recommended value for R_{TP} is 0.55 * 0.82 or 0.45.

If the permeable pavement is not the upstream most BMP in the treatment train, EMC_{TP} should be dependent on the M_{TP} effluent (mg/L) from the next upstream tributary BMP.

The annual volume treated by the BMP can be determined with appropriate modeling tools, including the MIDS calculator. Example values are shown below for a scenario using the MIDS calculator. For example, a permeable pavement system designed to capture 1 inch of runoff from impervious surfaces will capture 89 percent of annual runoff from a site with B (SM) soils. If an underdrain is in the system, this volume will have to be divided into the portion that infiltrates and the portion that is captured by the underdrain. The MIDS calculator can be used to determine these values.

Annual volume, expressed as a percent of annual runoff, treated by a BMP as a function of soil and water quality volume. See footnote[1] for how these were determined.
Link to this table

Soil	Water quality volume (V_{WQ}) (inches)				
	0.5	**0.75**	**1.00**	**1.25**	**1.50**
A (GW)	84	92	96	98	99

Soil	Water quality volume (V) (inches)				
	0.5	0.75	1.00	1.25	1.50
A (SP)	75	86	92	95	97
B (SM)	68	81	89	93	95
B (MH)	65	78	86	91	94
C	63	76	85	90	93

[1]Values were determined using the MIDS calculator. BMPs were sized to exactly meet the water quality volume for a 2 acre site with 1 acre of impervious, 1 acre of forested land, and annual rainfall of 31.9 inches.

The event (storm) event based TP credit (M_{TP_I}) for infiltrated runoff is given by

$M_{TP_I} = 2.72\ V_I\ EMC_{_{TP}}\ / 43,560$

where

V_I is the event-based volume infiltrated by the BMP, in cubic feet; and
a factor of 43,560 is used for conversion of volume from cubic feet to acre-ft.

The storm event based TP credit (M_{TP-F}) for filtered runoff is given by

$M_{TP - F} = R_{_{TP}}\ 2.72\ V_F\ EMC_{_{TP}}\ / 43560$

where

V_F is the event-based volume filtered by the BMP, in cubic feet

Example calculations for TSS and TP

NOTE: The MIDS calculator was used for the following examples. The performance goal was changed from the MIDS default of 1.1 inches to 1 inch.

Assume a permeable pavement system is designed to capture and treat 1 inch of runoff from a 1 acre impervious area. Note that in these calculations, the permeable pavement is considered part of the impermeable surface.

For this example, assume a 9000 square foot surface area at the top of the reservoir/subbase, a 9000 square foot area at the reservoir/soil subgrade, an underlying B soil with an infiltration rate of 0.45 inches per hour, a porosity of 0.4 cubic feet per cubic foot, a depth below the underdrain of 1 foot, a TSS EMC of 54.5 milligrams per liter, and a TP EMC of 0.3 milligrams per liter. With this depth below the underdrain, all the water can be infiltrated (3600 cubic feet per event; 2.3446 acre-feet per year). Annual TSS removal, in pounds, is given by

$2.72 (2.3446) (1) (54.5) = 347$

Annual TP removal is given by

$2.72 (2.3446) (1) (0.3) = 1.91$

If the depth below the underdrain was 0.5 feet instead of 1 foot, only half of the 1 inch performance goal is infiltrated, corresponding to an annual infiltration volume of 1.60 acre-feet. Note that the relationship between infiltration performance goal and annual volume infiltrated is not linear. The first step is to calculate the infiltration and filtered fractions of total volume captured by the BMP. The infiltrated fraction is 1.60/2.3446 or 0.68, leaving a filtered fraction of 0.32.

Annual TSS removal, in pounds, is given by

$(2.72 (2.3446) (0.68) (54.5)) + ((2.72 (2.3446) (0.32) (0.74) (54.5)) = 319$

The first term in parentheses corresponds with the infiltrated portion and equals about 236.3 pounds. The second term in parentheses corresponds with the filtered portion, having a removal efficiency of 0.74 (74 percent), for a total removal of about 82.3 pounds.

Annual TP removal, in pounds, is given by

$(2.72 (2.3446) (0.68) (0.3)) + ((2.72 (2.3446) (0.32) (0.55) (0.82) (0.3)) = 1.58$

The first term in parentheses corresponds with the infiltrated portion and equals about 1.30 pounds. The second term in parentheses corresponds with the filtered portion, having a particulate P fraction of 0.55, and a removal efficiency of 0.82 (82 percent) for the particulate fraction, for a total removal of about 0.28 pounds.

Methods for calculating credits

This section provides specific information on generating and calculating credits from permeable pavement for volume, Total Suspended Solids (TSS) and Total Phosphorus (TP). Stormwater runoff volume and pollution reductions ("credits") may be calculated using one of the following methods:

1. Quantifying volume and pollution reductions based on accepted hydrologic models
2. The Simple Method and MPCA Estimator
3. MIDS Calculator

4. Quantifying volume and pollution reductions based on values reported in literature
5. Quantifying volume and pollution reductions based on field monitoring

Credits based on models

Warning: The model selected depends on your objectives. For compliance with the Construction Stormwater permit, the model must be based on the assumption that an instantaneous volume is captured by the BMP.

Users may opt to use a water quality model or calculator to compute volume, TSS and/or TP pollutant removal for the purpose of determining credits. The available models described in the following sections are commonly used by water resource professionals, but are not explicitly endorsed or required by the Minnesota Pollution Control Agency. Furthermore, many of the models listed below cannot be used to determine compliance with the Construction Stormwater General permit since the permit requires the water quality volume to be calculated as an instantaneous volume.

Use of models or calculators for the purpose of computing pollutant removal credits should be supported by detailed documentation, including:

1. Model name and version
2. Date of analysis
3. Person or organization conducting analysis
4. Detailed summary of input data
5. Calibration and verification information
6. Detailed summary of output data

The following table lists water quantity and water quality models that are commonly used by water resource professionals to predict the hydrologic, hydraulic, and/or pollutant removal capabilities of a single or multiple stormwater BMPs. The table can be used to guide a user in selecting the most appropriate model for computing volume, TSS, and/or TP removal by the BMP. In using this table to identify models appropriate for permeable pavement, use the sort arrow on the table to select Infiltrator BMPs or Filter BMPs, depending on the type of permeable pavement BMP and the terminology used in the model.

Comparison of stormwater models and calculators. Additional information and descriptions for some of the models listed in this table can be found at this link. Note that the Construction Stormwater General Permit requires the water quality volume to be calculated as an instantaneous volume, meaning several of these models cannot be used to determine compliance with the permit.
Link to this table
Access this table as a Microsoft Word document: File:Stormwater Model and Calculator Comparisons table.docx.

Model name	BMP Category	Assess TP	Assess TSS	Assess volume	Comments

Model name	BMP Category						Assess TP removal?	Assess TSS removal?	Assess volume reduction?	Comments
	Constructed basin BMPs	Filter BMPs	Infiltrator BMPs	Swale or strip BMPs	Reuse	Manu- factured devices				
Center for Neighborhood Technology Green Values National Stormwater Management Calculator	X	X	X		X		No	No	Yes	Does not compute volume reduction fo some BMPs, including cisterns and tree trenche
CivilStorm							Yes	Yes	Yes	CivilStorm h an engineering library with many different types of BM to choose from. This li changes as new information becomes available.
EPA National Stormwater Calculator	X		X		X		No	No	Yes	Primary purpose is t assess reductions i stormwater volume.

Model name	BMP Category						Assess TP removal?	Assess TSS removal?	Assess volume reduction?	Comments
	Constructed basin BMPs	Filter BMPs	Infiltrator BMPs	Swale or strip BMPs	Reuse	Manu-factured devices				
EPA SWMM	X		X		X		Yes	Yes	Yes	User defines parameter that can be used to simulate generalized constituents
HydroCAD	X		X	X			No	No	Yes	Will assess hydraulics, volumes, an pollutant loading, but not pollutan reduction.
infoSWMM	X		X		X		Yes	Yes	Yes	User defines parameter that can be used to simulate generalized constituents
infoWorks ICM	X	X	X	X			Yes	Yes	Yes	
i-Tree-Hydro			X				No	No	Yes	Includes simple calculator fc rain gardens

Model name	BMP Category						Assess TP removal?	Assess TSS removal?	Assess volume reduction?	Comments
	Constructed basin BMPs	Filter BMPs	Infiltrator BMPs	Swale or strip BMPs	Reuse	Manu-factured devices				
i-Tree-Streets							No	No	Yes	Computes volume reduction fo trees, only.
LSPC	X		X	X			Yes	Yes	Yes	Though developed f HSPF, the USEPA BMP Web Toolkit can be used with LSPC tc model structural BMPs such a detention basins, or infiltration BMPs that represent source control facilities, which captu runoff from small impervious areas (e.g., parking lots or rooftops)

Model name	BMP Category						Assess TP removal?	Assess TSS removal?	Assess volume reduction?	Comments
	Constructed basin BMPs	Filter BMPs	Infiltrator BMPs	Swale or strip BMPs	Reuse	Manu-factured devices				
MapShed	X	X	X	X			Yes	Yes	Yes	Region-specific inpu data not available fo Minnesota but user car create this data for any region.
MCWD/MWMO Stormwater Reuse Calculator					X		Yes	No	Yes	Computes storage volume for stormwater reuse syster
Metropolitan Council Stormwater Reuse Guide Excel Spreadsheet					X		No	No	Yes	Computes storage volume for stormwater reuse systems. Us 30-year precipitatior data specifi to Twin Cites region of Minnesota.

Model name	BMP Category						Assess TP removal?	Assess TSS removal?	Assess volume reduction?	Comments
	Constructed basin BMPs	Filter BMPs	Infiltrator BMPs	Swale or strip BMPs	Reuse	Manu-factured devices				
MIDS Calculator	X	X	X	X	X	X	Yes	Yes	Yes	Includes use defined feature that can be used for manufactur devices and other BMPs.
MIKE URBAN (SWMM or MOUSE)	X		X		X		Yes	Yes	Yes	User define parameter that can be used to simulate generalized constituents
P8	X		X	X		X	Yes	Yes	Yes	
PCSWMM	X		X		X		Yes	Yes	Yes	User define parameter that can be used to simulate generalized constituents
PLOAD	X	X	X	X		X	Yes	Yes	No	User-define practices wi user-specifi removal percentages

Model name	BMP Category						Assess TP removal?	Assess TSS removal?	Assess volume reduction?	Comments
	Constructed basin BMPs	Filter BMPs	Infiltrator BMPs	Swale or strip BMPs	Reuse	Manu-factured devices				
PondNet	X						Yes	No	Yes	Flow and phosphorus routing in pond networks.
PondPack	X		[				No	No	Yes	PondPack ca calculate fir flush volum but does no model pollutants. I can be used to calculate pond infiltration.
RECARGA			X				No	No	Yes	
SELECT	X	X	X	X		X	Yes	Yes	Yes	User define parameter that can be used to simulate generalized constituents

Model name	BMP Category						Assess TP removal?	Assess TSS removal?	Assess volume reduction?	Comments
	Constructed basin BMPs	Filter BMPs	Infiltrator BMPs	Swale or strip BMPs	Reuse	Manu-factured devices				
SHSAM						X	No	Yes	No	Several flow through structures including standard sumps, and proprietary systems suc as CDS, Stormcepto and Vortech systems
SUSTAIN	X	X	X	X	X		Yes	Yes	Yes	Categorizes BMPs into Point BMPs, Linear BMPs and Area BMPs
SWAT	X	X	X				Yes	Yes	Yes	Model offer many agricultural BMPs and practices, bu limited urba BMPs at this time.

Model name	BMP Category						Assess TP removal?	Assess TSS removal?	Assess volume reduction?	Comments
	Constructed basin BMPs	Filter BMPs	Infiltrator BMPs	Swale or strip BMPs	Reuse	Manu-factured devices				
Virginia Runoff Reduction Method	X	X	X	X	X	X	Yes	No	Yes	Users input Event Mean Concentrati (EMC) pollutant removal percentages for manufactur devices.
WARMF	X	X					Yes	Yes	Yes	Includes agriculture BMP assessment tools. Compatible with USEPA Basins

Model name	BMP Category						Assess TP removal?	Assess TSS removal?	Assess volume reduction?	Comments
	Constructed basin BMPs	Filter BMPs	Infiltrator BMPs	Swale or strip BMPs	Reuse	Manu-factured devices				
WinHSPF	X		X	X			Yes	Yes	Yes	USEPA BMP Web Toolkit available to assist with implementi structural BMPs such a detention basins, or infiltration BMPs that represent source control facilities, which captu runoff from small impervious areas (e.g., parking lots or rooftops)
WinSLAMM	X	X	X	X			Yes	Yes	Yes	

Model name	BMP Category						Assess TP removal?	Assess TSS removal?	Assess volume reduction?	Comments
	Constructed basin BMPs	Filter BMPs	Infiltrator BMPs	Swale or strip BMPs	Reuse	Manu-factured devices				
XPSWMM	X		X		X		Yes	Yes	Yes	User defines parameter that can be used to simulate generalized constituents

The Simple Method and MPCA Estimator

The Simple Method is a technique used for estimating storm pollutant export delivered from urban development sites. Pollutant loads are estimated as the product of mean pollutant concentrations and runoff depths over specified periods of time (usually annual or seasonal). The method was developed to provide an easy yet reasonably accurate means of predicting the change in pollutant loadings in response to development. Ohrel (2000) states: "In general, the Simple Method is most appropriate for small watersheds (<640 acres) and when quick and reasonable stormwater pollutant load estimates are required". Rainfall data, land use (runoff coefficients), land area, and pollutant concentration are needed to use the Simple Method. For more information on the Simple Method, see The Simple method to Calculate Urban Stormwater Loads or The Simple Method for estimating phosphorus export.

Some simple stormwater calculators utilize the Simple Method (STEPL, Watershed Treatment Model). The MPCA developed a simple calculator for estimating load reductions for TSS, total phosphorus, and bacteria. Called the **MPCA Estimator**, this tool was developed specifically for complying with the MS4 General Permit TMDL annual reporting requirement. The MPCA Estimator provides default values for pollutant concentration, runoff coefficients for different land uses, and precipitation, although the user can modify these and is encouraged to do so when local data exist. The user is required to enter area for different land uses and area treated by BMPs within each of the land uses. BMPs include infiltrators (e.g. bioinfiltration, infiltration basin, tree trench, permeable pavement, etc.), filters (biofiltration, sand filter, green roof), constructed ponds and wetlands, and swales/filters. The MPCA Estimator includes standard removal efficiencies for these BMPs, but the user can modify those values if better data are available. Output from the calculator is given as a load reduction (percent, mass, or number of bacteria) from the original estimated load.

Warning: The MPCA Estimator should not be used for modeling a stormwater system or selecting BMPs.

Because the MPCA Estimator does not consider BMPs in series, makes simplifying assumptions about runoff and pollutant removal processes, and uses generalized default information, it should only be used for estimating pollutant reductions from an estimated load. It is not intended as a decision-making tool.

Download MPCA Estimator here: File:MPCA Estimator.xlsx

A quick guide for the estimator is available Quick Guide: MPCA Estimator tab.

MIDS Calculator

The Minimal Impact Design Standards (MIDS) best management practice (BMP) calculator is a tool used to determine stormwater runoff volume and pollutant reduction capabilities of various low impact development (LID) BMPs. The MIDS calculator estimates the stormwater runoff volume reductions for various BMPs and annual pollutant load reductions for total phosphorus (including a breakdown between particulate and dissolved phosphorus) and total suspended solids (TSS). The calculator was intended for use on individual development sites, though capable modelers could modify its use for larger applications.

Minimal Impact Design Standards
for enhancing stormwater management in Minnesota

Download the MIDS Calculator

The MIDS calculator is designed in Microsoft Excel with a graphical user interface (GUI), packaged as a windows application, used to organize input parameters. The Excel spreadsheet conducts the calculations and stores parameters, while the GUI provides a platform that allows the user to enter data and presents results in a user-friendly manner.

Detailed guidance and examples have been developed for all BMPs in the calculator, including permeable pavement. An overview of individual input parameters and workflows is presented in the MIDS Calculator User Documentation.

Credits based on reported literature values

A simplified approach to computing a credit would be to apply a reduction value found in literature to the pollutant mass load or concentration (EMC) of the permeable pavement system. Concentration reductions resulting from treatment can be converted to mass reductions if the volume of stormwater treated is known.

Designers may use the pollutant reduction values reported in this manual or may research values from other databases and published literature. Designers who opt for this approach should

- select the median value from pollutant reduction databases that report a range of reductions, such as from the International BMP Database;

- select a pollutant removal reduction from literature that studied a permeable pavement system with site characteristics and climate similar to the device being considered for credits;
- review the article to determine that the design principles of the studied permeable pavement system are close to the design recommendations for Minnesota, as described in this manual and/or by a local permitting agency; and
- give preference to literature that has been published in a peer-reviewed publication.

The following references summarize pollutant reduction values from multiple studies or sources that could be used to determine credits. Users should note that there is a wide range of monitored pollutant removal effectiveness in the literature. Before selecting a literature value, users should compare the characteristics of the monitored site in the literature against the characteristics of the proposed permeable pavement system, considering such conditions as watershed characteristics, BMP sizing, soil infiltration rates, and climate factors.

- BMP Performance Analysis. Prepared for US EPA Region 1, Boston MA.
  - Appendix B provides pollutant removal performance curves
  - Provides values for TP, TSS, and Zn.
  - Pollutant removal broken down according to land use.
  - Applicable to Infiltration Trench, Infiltration Basin, Bioretention, Grass Swale, Wet Pond, and Porous Pavement.
- Brown, Chris; Angus Chu; Bert van Duin; Caterina Valeo. 2009. Characteristics of Sediment Removal in Two Types of Permeable Pavement. Water Qual. Res. J. Can. Volume 44, No. 1, 59-70.
- The Illinois Green Infrastructure Study
  - Figure ES-1 summarizes BMP effectiveness
  - Provides values for TN, TSS, peak flows / runoff volumes
  - Applicable to Permeable Pavements, Constructed Wetlands, Infiltration, Detention, Filtration, and Green Roofs
- International Stormwater Best Management Practices (BMP) Database Pollutant Category Summary Statistical Addendum: TSS, Bacteria, Nutrients, and Metals
  - Provides values for TSS removal
  - Compilation of BMP performance studies published through 2011.
  - Provides values for TSS, Bacteria, Nutrients, and Metals
  - Applicable to grass strips, bioretention, bioswales, detention basins, green roofs, manufactured devices, media filters, porous pavements, wetland basins, and wetland channels.
- New Hampshire Department of Environmental Services. 2008. New Hampshire Stormwater Manual. Volume 2 Appendix B.
  - Provides values for volume, TSS, TN, and TP removal
  - In addition to permeable pavement, includes data for stormwater ponds, stormwater wetlands, infiltration practices, filtering practices, treatment swales, vegetated buffers, and pre-treatment practices
- New Jersey Department of Environmental Protection. 2004. New Jersey Stormwater BMP Manual. Standards for Pervious Paving Systems. Chapter 9.7.

- Provides values for TSS removal

- North Carolina Department of Environment and Natural Resources. Water Quality Division. 2012. Stormwater BMP Manual & BMP Forms. Chapter 18. Permeable Pavement.
  - Provides values for TSS, TN, and TP removal based on calculations of impervious surface converted to permeable pavement
- Tennis, Paul D.; Michael L. Leming; David J. Akers. 2004. Pervious Concrete Pavements. EB302.02, Portland Cement Association and National Ready Mixed Concrete Association.
  - Provides values for TSS, TN, and TP removal
- Tota-Maharaj, K. and Scholz, M. 2010. Efficiency of permeable pavement systems for the removal of urban runoff pollutants under varying environmental conditions. Environ. Prog. Sustainable Energy, 29: 358–369. doi: 10.1002/ep.10418
  - Provides removal efficiencies for total coliforms, Escherichia coli, and fecal Streptococci, as well as the key nutrients ammonia-nitrogen, nitrate nitrogen, and ortho-phosphate phosphorus, and physical variables such as suspended solids and turbidity
- USEPA. Stormwater Menu of BMPs. Permeable Pavements. 2009.
  - See Table 2 for list of monitored pollutant removal for permeable pavement
  - Provides values for TSS, Metals, and Nutrients

Credits based on field monitoring

Field monitoring may be used to calculate stormwater credits in lieu of desktop calculations or models/calculators as described. Careful planning is HIGHLY RECOMMENDED before commencing a program to monitor the performance of a BMP. The general steps involved in planning and implementing BMP monitoring include the following.

1. Establish the objectives and goals of the monitoring.
   a. Which pollutants will be measured?
   b. Will the monitoring study the performance of a single BMP or multiple BMPs?
   c. Are there any variables that will affect the BMP performance? Variables could include design approaches, maintenance activities, rainfall events, rainfall intensity, etc.
   d. Will the results be compared to other BMP performance studies?
   e. What should be the duration of the monitoring period? Is there a need to look at the annual performance vs the performance during a single rain event? Is there a need to assess the seasonal variation of BMP performance?
2. Plan the field activities. Field considerations include:
   a. Equipment selection and placement
   b. Sampling protocols including selection, storage, delivery to the laboratory
   c. Laboratory services
   d. Health and Safety plans for field personnel

    e. Record keeping protocols and forms
    f. Quality control and quality assurance protocols

3. Execute the field monitoring
4. Analyze the results

The following guidance manuals have been developed to assist BMP owners and operators on how to plan and implement BMP performance monitoring.

Urban Stormwater BMP Performance Monitoring

Geosyntec Consultants and Wright Water Engineers prepared this guide in 2009 with support from the USEPA, Water Environment Research Foundation, Federal Highway Administration, and the Environment and Water Resource Institute of the American Society of Civil Engineers. This guide was developed to improve and standardize the protocols for all BMP monitoring and to provide additional guidance for Low Impact Development (LID) BMP monitoring. Highlighted chapters in this manual include:

- Chapter 2: Designing the Program
- Chapters 3 & 4: Methods and Equipment
- Chapters 5 & 6: Implementation, Data Management, Evaluation and Reporting
- Chapter 7: BMP Performance Analysis
- Chapters 8, 9, & 10: LID Monitoring

Evaluation of Best Management Practices for Highway Runoff Control (NCHRP Report 565)

AASHTO (American Association of State Highway and Transportation Officials) and the FHWA (Federal Highway Administration) sponsored this 2006 research report, which was authored by Oregon State University, Geosyntec Consultants, the University of Florida, and the Low Impact Development Center. The primary purpose of this report is to advise on the selection and design of BMPs that are best suited for highway runoff. The document includes the following chapters on performance monitoring that may be a useful reference for BMP performance monitoring, especially for the performance assessment of a highway BMP:

- Chapter 4: Stormwater Characterization
    - 4.2: General Characteristics and Pollutant Sources
    - 4.3: Sources of Stormwater Quality data
- Chapter 8: Performance Evaluation
    - 8.1: Methodology Options
    - 8.5: Evaluation of Quality Performance for Individual BMPs
    - 8.6: Overall Hydrologic and Water Quality Performance Evaluation
- Chapter 10: Hydrologic Evaluation

- 10.5: Performance Verification and Design Optimization

Investigation into the Feasibility of a National Testing and Evaluation Program for Stormwater Products and Practices.

In 2014 the Water Environment Federation released this White Paper that investigates the feasibility of a national program for the testing of stormwater products and practices. The information contained in this White Paper would be of use to those considering the monitoring of a manufactured BMP. The report does not include any specific guidance on the monitoring of a BMP, but it does include a summary of the existing technical evaluation programs that could be consulted for testing results for specific products (see Table 1 on page 8).

Caltrans Stormwater Monitoring Guidance Manual (Document No. CTSW-OT-13-999.43.01)

The most current version of this manual was released by the State of California, Department of Transportation in November 2013. As with the other monitoring manuals described, this manual does include guidance on planning a stormwater monitoring program. However, this manual is among the most thorough for field activities. Relevant chapters include:

- Chapter 4: Monitoring Methods and Equipment
- Chapter 5: Analytical Methods and Laboratory Selection
- Chapter 6: Monitoring Site Selection
- Chapter 8: Equipment Installation and Maintenance
- Chapter 10: Pre-Storm Preparation
- Chapter 11: Sample Collection and Handling
- Chapter 12: Quality Assurance / Quality Control
- Chapter 13: Laboratory Reports and Data Review
- Chapter 15: Gross Solids Monitoring

Optimizing Stormwater Treatment Practices: A Handbook of Assessment and Maintenance

This online manual was developed in 2010 by Andrew Erickson, Peter Weiss, and John Gulliver from the University of Minnesota and St. Anthony Falls Hydraulic Laboratory with funding provided by the Minnesota Pollution Control Agency. The manual advises on a four-level process to assess the performance of a Best Management Practice, involving:

- Level 1: Visual Inspection
- Level 2: Capacity Testing
- Level 3: Synthetic Runoff Testing
- Level 4: Monitoring
- Level 1 activities do not produce numerical performance data that could be used to obtain a stormwater management credit. BMP owners and operators who are interested in using data obtained from Levels 2 and 3 should consult with the MPCA or other regulatory agency to determine if the results are appropriate for credit calculations. Level 4, Monitoring, is the method most frequently used for assessment of the performance of a BMP.

Use these links to obtain detailed information on the following topics related to BMP performance monitoring:

- Water Budget Measurement
- Sampling Methods
- Analysis of Water and Soils
- Data Analysis for Monitoring

Other pollutants

Permeable pavements provide removal of sediment (TSS), nutrients (phosphorus and nitrogen), and metals through filtration, infiltration, and soil adsorption. Temperature control occurs in the stone reservoir/subbase and soil subgrade. Phosphorus, metals, and hydrocarbons are adsorbed onto soils within the subgrade. In addition, nutrients such as phosphorus and nitrogen may be biologically degraded.

According to the International BMP Database, studies have shown that permeable pavements are effective at reducing concentration of pollutants including solids, bacteria, metals, and nutrients. A compilation of the pollutant removal capabilities from a review of literature of permeable pavement studies are summarized in the table below.

Relative pollutant reduction from permeable pavement systems for metals, nitrogen, bacteria, and organics.
Link to this table

Pollutant	Constituent	Treatment capabilities[1]
Metals[2]	Cadmium, Chromium, Copper, Zinc, Lead, Nickel	Medium/High
Nitrogen	Total nitrogen, Total Kjeldahl nitrogen	Medium/High
Bacteria	Fecal coliform, e. coli	Insufficient data
Organics		Medium

[1] Low: < 30%; Medium: 30 to 65%; High: >65%

[2] Results are for total metals only

References and suggested reading

- Brown, Chris; Angus Chu; Bert van Duin; Caterina Valeo. 2009. Characteristics of Sediment Removal in Two Types of Permeable Pavement. Water Qual. Res. J. Can. Volume 44, No. 1, 59-70.

- Geosyntec and Wright Water Engineers. 2012. International Stormwater Best Management Practices (BMP) Database Pollutant Category Summary Statistical Addendum: TSS, Bacteria, Nutrients, and Metals. Prepared under Support from WERF, FHWA, EWRI/ASCE and EPA. July 2012.
- New Hampshire Department of Environmental Services. 2008. New Hampshire Stormwater Manual. Volume 2 Appendix B.
- New Jersey Department of Environmental Protection. 2004. New Jersey Stormwater BMP Manual. Standards for Pervious Paving Systems. Chapter 9.7.
- North Carolina Department of Environment and Natural Resources. Water Quality Division. 2012. Stormwater BMP Manual & BMP Forms. Chapter 18. Permeable Pavement.
- Tennis, Paul D.; Michael L. Leming; David J. Akers. 2004. Pervious Concrete Pavements. EB302.02, Portland Cement Association and National Ready Mixed Concrete Association.
- Tota-Maharaj, K. and Scholz, M. 2010. Efficiency of permeable pavement systems for the removal of urban runoff pollutants under varying environmental conditions. Environ. Prog. Sustainable Energy, 29: 358–369. doi: 10.1002/ep.10418
- USEPA. Stormwater Menu of BMPs. Permeable Pavements. 2009.

Case studies for permeable pavement

This page contains interesting stories about permeable pavement. If you have a good story, send us a link using the Comment box and we will consider including it on this page.

Green Infrastructure: Permeable pavement can be an important tool for retention and detention of stormwater runoff. Permeable pavement may provide additional benefits, including reducing the need for de-icing chemicals, and providing a durable and aesthetically pleasing surface.

Caution: Reference herein to any specific commercial products, process, or service by trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the Minnesota Pollution Control Agency.

There are hundreds of permeable pavement applications in Minnesota. Examples will be updated as more information is gathered. For now, here are a few examples:

- The City of St. Paul constructed two way, off street bike trails along portions of Jackson Street, Kellogg Boulevard, St. Peter Street, 9th Street and 10th Street using porous asphalt.
- The City of Shoreview has 5 permeable pavement installations. The Dale Street Alley has 12 foot wide pervious concrete; the intersection near Shamrock Park has porous asphalt; the Woodbridge Neighborhood has pervious concrete; the public works facility has pervious concrete and the

Oakridge Avenue project uses a 20 foot wide permeable concrete block system (PaveDrain). For information on any of these projects, contact Shoreview City Public Works Director, Mark Maloney at mmaloney@shoreviewmn.gov. The City of Shoreview has additional information about permeable roadways on their web site.

A bike lane in St Paul MN

- Ramsey Washington Metro Watershed District office has 2 permeable pavement installations. Porous asphalt was installed at the District Office in 2005. For details about this application, go to the Watershed District's web site. Additionally, in 2014, the District installed a PaveDrain system on an acquired portion of their existing property. PaveDrain permeable pavers are a relatively new product and the District was interested in using them as a demonstration project.
- The City of Waconia has two permeable concrete block (PaveDrain) systems in place. One is located at Fountain Park and the other is at the Iron Tap Brewery. For more information, contact Craig Eldred, City of Waconia Public Works Director at celdred@waconia.org
- The City of Maplewood has three permeable pavement systems: Maplewood Public Works parking lot, Geranium Park parking lot and Maplewood Nature Center.
- City of Plymouth porous pavement and reinforced turf
- The Effectiveness of Permeable Pavers on page 22 of the November edition of the Minnesota Nursery and Landscape Association newsletter.
- Holey pavement–it excites me

Permeable Pavers at Ramsey Washington Metro Watershed District. Photo Courtesy of Paige Ahlborg

Green Infrastructure benefits of permeable pavement

Green Infrastructure benefits of permeable pavement

Summary of permit requirements for infiltration

Green Infrastructure benefits of permeable pavement

Permeable pavement photo gallery

Click on an image for enlarged view.

Porous concrete

Porous asphalt

Porous asphalt

Permeable pavers

Permeable pavers

Additional considerations for permeable pavement

Green Infrastructure: Permeable pavement can be an important tool for retention and detention of stormwater runoff. Permeable pavement may provide additional benefits, including reducing the need for de-icing chemicals, and providing a durable and aesthetically pleasing surface.

Compliance with the Americans with Disabilities Act (ADA)

All permeable pavements are ADA compliant. PICP is compliant if designs are used with joints less than ½ inch wide.

Groundwater protection and underground injection control permits

The Safe Drinking Water Act regulates the infiltration of stormwater in certain situations pursuant to the Underground Injection Control (UIC) Program, which is administered either by the US EPA or a delegated state groundwater protection agency. The US EPA (USEPA 2008) determined that permeable pavement installations are not classified as Class V injection wells since they are always wider than they are deep. There may be an exception in karst terrain if the discharge from permeable pavement is directed to an improved sinkhole, although this would be uncommon.

Air and runoff temperature

Permeable pavement appears to have some value in reducing summer runoff temperatures which can be important in watersheds with sensitive cold-water fish populations (Hunt 2011). The temperature reduction effect is greatest when runoff is infiltrated into reservoir layer when underdrains are used. All permeable pavements exhibit cooler summer temperatures than their impervious counterparts. For example, a recent study showed that porous asphalt showed lower nighttime temperatures when compared with materials that have a similar or higher albedo. This was attributed to the insulating properties of porous asphalt due to its high air void content (Stempihar 2011). Pervious concrete and PICP can meet the solar reflectance index (SRI) of 29.

Sustainable rating systems

All permeable pavements support sustainable rating systems such as LEED and others plus sustainable transportation rating systems such as those published by the Institute for Sustainable Infrastructure (Envision), Federal Highway Administration (INVEST), and the University of Washington (Greenroads).

Certification

Warning: The MPCA does not endorse any specific product or service, including trainings, workshops, or other similar practices or events

As previously noted, the pervious concrete and PICP industry associations offer education and certification of permeable pavement contractors, i.e., the National Ready Mix Concrete Association (NRMCA) and the Interlocking Concrete Pavement Institute (ICPI). Porous asphalt does not require unique materials and can be installed by most paving equipment. In addition, all plants producing hot-mix asphalt are required to be certified by MnDOT. Industry-trained and experienced supervisory personnel should be required on all jobsites and requirements written into project specifications. A specifications requirement can be contractor submittals demonstrating experience with previous projects.

For design professionals, industry and professional associations offer in-person and online continuing education programs on design, construction and maintenance of permeable pavements. Many of these programs are registered with continuing education programs offered for civil engineering professional development hours, the American Institute of Architects and the American Society of Landscape Architecture continuing education

systems, and the Green Building Certificate Institute Credential Maintenance Program for LEED® accredited professionals. Designers are encouraged to participate in these programs.

Industry associations provide literature and design software for design professionals. The National Asphalt Pavement Association offers “Porous Asphalt Pavements for Stormwater Management, Design, Construction, and Maintenance Guide” (Hansen 2008). The Minnesota Asphalt Pavement Association has guidance on their website. The American Concrete Pavement Institute has design software called PerviousPave for design of pervious concrete pavement. The software can be downloaded from their website. Specifications for the design of pervious concrete are provided by the American Concrete Institute (ACI) in ACI 522.1-08 “Specification for Pervious Concrete Pavement”. A report titled ACI 522R-10 “Report on Pervious Concrete” is also available. ICPI offers a course called “Permeable Interlocking Concrete Pavements” covering design, specifications, construction, and maintenance. ICPI also offers Permeable Design Pro software for PICP structural and hydrologic design.

Links for permeable pavement

- Minnehaha Creek Watershed District has an informative video on installing a permeable paver driveway.

References for permeable pavement

- American Association of State highway and Transportation Officials (AASHTO). 1993. *Guide for Design of Pavement Structures*, American Association of State Highway and Transportation Officials, Washington, DC.
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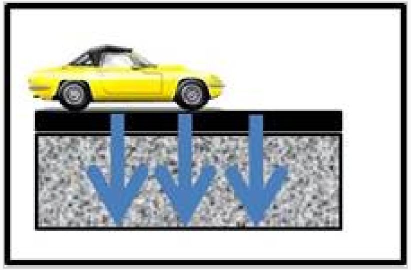
Requirements, recommendations and information for using permeable pavement BMPs in the MIDS calculator

For permeable pavement, stormwater runoff captured by the BMP and stored below the underdrain (if underdrain is present) is infiltrated into the underlying soil between rain events. All pollutants in the infiltrated stormwater are credited as being reduced. Pollutants in stormwater captured by the BMP but entering the underdrain are treated as they pass through the filter media and out the underdrain.

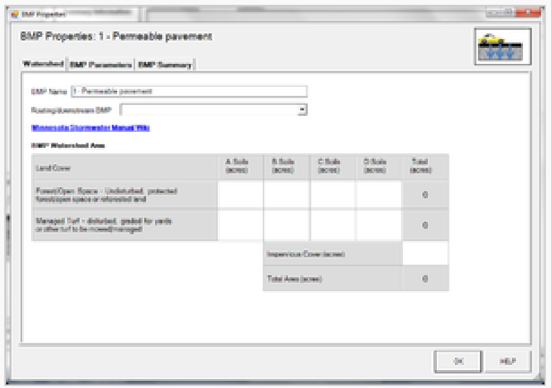

MIDS calculator symbol for permeable pavement.

MIDS calculator user inputs for permeable pavement

For permeable pavement systems, the user must input the following parameters to calculate the volume and pollutant load reductions associated with the BMP.

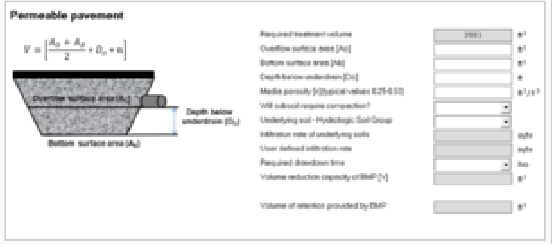
- **Watershed tab**

- BMP Name: this cell is auto-filled but can be changed by the user.
- Routing/downstream BMP: if this BMP is part of a treatment train and water is being routed from this BMP to another BMP, the user selects the name of the BMP from the dropdown box to which water is being routed. All water must be routed to a single downstream BMP. The User must include the BMP receiving the routed water in the Schematic or the BMP will not appear in the dropdown box.
- BMP Watershed Area: BMP watershed areas are the areas draining directly to the BMP. Values can be added for four soil types (Hydrologic Soil Groups (HSG) A, B, C, D) and for three Land Cover types (Forest/Open Space, Managed Turf and impervious area). The Impervious Cover includes the surface area of the permeable pavement and impervious area in the watershed that drains directly to the permeable pavement BMP. Units are in acres.



MIDS calculator screen shot of watershed tab for permeable pavement.

- **BMP Parameters tab**
  - Surface area at underdrain (A_U): This is the surface area of the BMP at the invert of the underdrain. If an underdrain is not present, it is the surface area of the permeable pavement. The user inputs this value in square feet. The calculator will display the surface area in acres for comparison with the watershed impervious cover acres entered for the BMP.
  - Bottom surface area (A_B): This is the surface area at the bottom of the engineered media. It represents the area where the engineered media changes to native soils. The user inputs this value in square feet.
  - Depth below underdrain (D_U): This is the depth below the underdrain to the native soils. If no underdrain is present, this is the thickness of the engineered media.
  - Media porosity (n): This is the ratio of pore space in the engineered media to the total volume of the engineered media. Units are volume/volume (e.g., cubic centimeters per cubic centimeter). If various types of media are used in the BMP, this value should be an average of the media installed between the underdrain and the native soils. Click here to see values for porosity based on soil type.
  - Will subsoil require compaction?: This is a YES/NO question. Select YES if compaction of the soil subgrade is needed to support vehicular loads. This selection does not affect the calculation of volume or pollutant reduction credits, but will likely reduce the infiltration rates of the underlying soils and the associated volume and pollutant credits. The USER should consider selecting a lower infiltration rate if the subsoil is compacted.
  - Underlying soil - Hydrologic Soil Group: The user selects the most restrictive soil (lowest hydraulic conductivity) within 5 feet of the soil/media interface in the permeable pavement. There are 14 soil options that fall into 4 different Hydrologic Soil Groups (Hydrologic Soil Group (HSG) A, B, C, or D) for the user. Once a soil type is selected, the corresponding infiltration rate will populate in the *Infiltration rate of underlying soils* field. The user may also select *User Defined*. This selection will activate the *User Defined Infiltration Rate* cell allowing the user to enter a different value from the values in the predefined selection list. The maximum allowable infiltration rate is 1.63 inches per hour.



MIDS calculator screen shot of BMP Parameters tab for permeable pavement.

- Required drawdown time (hrs): This is the time in which the stormwater captured by the BMP must drain into the underlying soil/media. The user selects from predefined values of 48 or 24 hours. The MPCA Construction Stormwater General Permit requires drawdown within 48 hours, but 24 hours is Highly Recommended when discharges are to a trout stream. The calculator uses the underlying soil infiltration rate and the *Depth below underdrain* to check if the BMP is meeting the drawdown time requirement. The user will encounter an error and be required to enter a new *Depth below underdrain* if the water stored in the BMP cannot drawdown in the required time.

- **BMP Summary Tab**: The BMP Summary tab summarizes the volume and pollutant reductions provided by the specific BMP. It details the performance goal volume reductions and annual average volume, dissolved P, particulate P, and TSS load reductions. Included in the summary are the total volume and pollutant loads received by the BMP from its direct watershed, from upstream BMPs and a combined value of the two. Also included in the summary are the volume and pollutant load reductions provided by the BMP, in addition to the volume and pollutant loads that exit the BMP through the outflow. This outflow load and volume is what is routed to the downstream BMP if one is defined in the Watershed tab. Finally, percent reductions are provided for the percent of the performance goal achieved, percent annual runoff volume retained, total percent annual particulate phosphorus reduction, total percent annual dissolved phosphorus reduction, total percent annual TP reduction, and total percent annual TSS reduction.

Model input requirements and recommendations

The following are requirements or recommendations for inputs into the MIDS calculator. If the following are not met, an error message will inform the user to change the input to meet the requirement.

- The *Surface area at the underdrain* of the permeable pavement cannot be greater than the total impervious area routed to the permeable pavement.
- The total contributing impervious area cannot be more than 5 times the surface area of the permeable pavement. Since the permeable pavement itself is treated as an impervious surface in the calculator, the maximum run-on area to a permeable pavement system from traditional impervious surfaces must be equal to or less than four times the area of the permeable pavement. For example, a parking lot with 10,000 square foot of permeable pavement can also have a 40,000 square foot or less run-on area from a traditional parking lot. In this example, the maximum impervious area input to the calculator is 50,000 square feet.
- The water underneath the underdrain must meet the drawdown time requirement specified. The drawdown time requirement is checked by comparing the user defined drawdown time with the calculated drawdown time (DDT_{calc}), given by

$DDT_{calc} = D_U / (I_R / 12)$

Where

D_U is the depth below the underdrain (ft); and
I_R is the infiltration rate of the native soils (inches/hr).

- Infiltration rates of the underlying soils are restricted to being below 1.63 inches per hour.
- The *Bottom surface area* cannot be greater than the *Surface area at underdrain*.

Methodology

Required Treatment Volume

Required treatment volume, or the volume of stormwater runoff delivered to the BMP, equals the performance goal (1.1 inches or user-specified performance goal) times the impervious area draining to the BMP, plus any water routed to the BMP from an upstream BMP. This stormwater is delivered to the BMP instantaneously.

Volume Reduction

The volume reduction achieved by a BMP compares the capacity of the BMP to the required treatment volume. The *Volume reduction capacity of BMP* is calculated using BMP inputs provided by the user. For this BMP the volume reduction credit is equal to the amount of water that can be instantaneously captured by the BMP in the media below the underdrain. The capture volume (V) is therefore given by

$V= (A_U + A_B)) / 2 * n * D_U$

Where:

A_U is the surface area at the underdrain in ft^2
A_B is the surface area at the bottom of the basin in ft^2
n is the media porosity of the soils
D_U is the depth of the media below the underdrain in ft

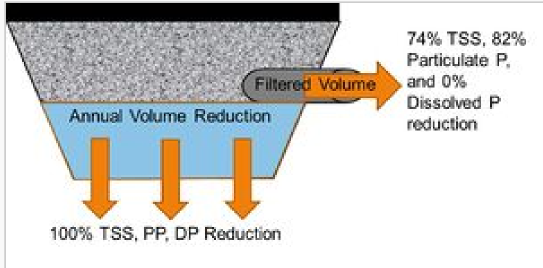
The *Volume of retention provided by BMP* is the amount of volume credit the BMP provides toward the performance goal. This value is equal to the lesser of the *Volume reduction capacity of BMP* calculated using the above method or the *Required treatment volume*. This check makes sure that the BMP is not getting more credit than necessary to meet the performance goal. For example, if the BMP is oversized the user will only receive credit for the *Required treatment volume* routed to the BMP, which corresponds with meeting the performance goal for the site .

Pollutant Reduction

Pollutant load reductions are calculated on an annual basis. Therefore, the first step in calculating annual pollutant load reductions is converting the *Volume reduction capacity of BMP*, which is an instantaneous volume reduction, to an annual volume reduction percentage. This is accomplished through the use of performance curves developed from multiple modeling scenarios. The performance curves use the *Volume reduction capacity of BMP*, the infiltration rate of the underlying soils, the contributing watershed percent impervious area, and the size of the contributing watershed to

calculate a percent annual volume reduction. While oversizing a BMP above the *Required treatment volume* will not provide additional credit towards the performance goal volume, it may provide additional pollutant reduction.

A 100 percent removal is credited for all pollutants associated with the reduced volume of stormwater since these pollutants are either attenuated within the media or pass into the underlying soil with infiltrating water. Stormwater that is not infiltrated is assumed to flow through the filter media and out the underdrain. A 74 percent TSS, 82 percent particulate phosphorus, and 0 percent dissolved phosphorus removal is applied to the filtered stormwater. A schematic of the removal rates can be seen in the sidebar.



Schematic showing how pollutant reductions are achieved for permeable pavement in the MIDS calculator

NOTE: The user can modify event mean concentrations (EMCs) on the Site Information tab in the calculator. Default concentrations are 54.5 milligrams per liter for total suspended solids (TSS) and 0.3 milligrams per liter for total phosphorus (particulate plus dissolved). The calculator will notify the user if the default is changed. Changing the default EMC will result in changes to the total pounds of pollutant reduced.

Routing

A permeable pavement BMP can be routed to any other BMP, except for a green roof and a swale side slope or any BMP that would cause stormwater to be rerouted back to the infiltration basin already in the stormwater runoff treatment sequence. All BMPs can be routed to the permeable pavement, except for a swale side slope.

Assumptions

The following general assumptions apply in calculating the credit for a permeable pavement system. If these assumptions are not followed, the volume and pollutant reduction credits cannot be applied.

- The permeable pavement is properly designed.
- The permeable pavement was properly constructed, consistent with the design criteria.
- The permeable pavement is properly maintained. The performance of the permeable pavement should be regularly assessed.

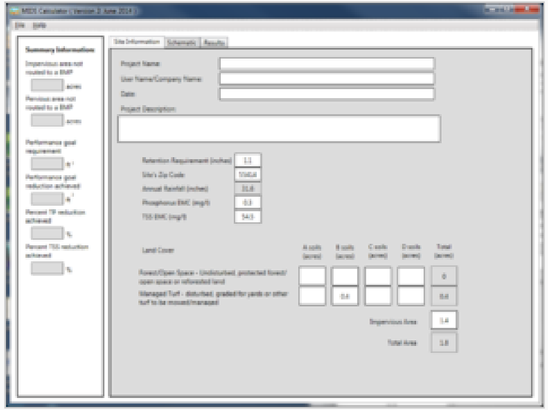
Example application in the MIDS calculator (Version 2)

Half of an existing 1.4 acre parking lot is going to be converted to permeable pavement. The entire parking lot (1.4 acres) plus 0.4 acres of pervious area (Turf Area) surrounding the parking lot will drain into the permeable pavement. The soils across the area have a unified soils classification of SM (HSG type B soil). An underdrain will be installed under the permeable pavement 0.5 feet above the native soils. Following the MPCA Construction

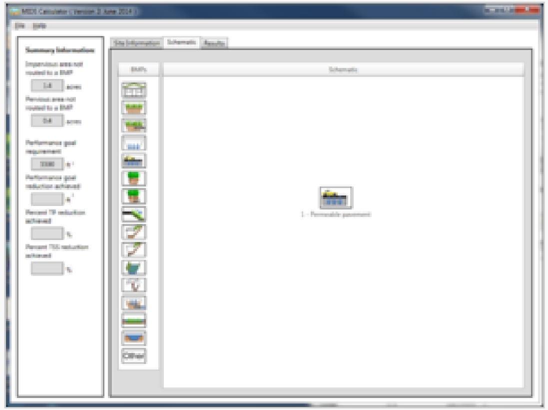
Schematic illustrating the site conditions for the permeable pavement example. In this example, there are 0.7 acres of impervious parking lot draining to a 0.7 acre permeable pavement area. A 0.4 acre turf area surrounds the site. The permeable pavement is included in the site impervious area. See Step 1.

Stormwater General Permit requirement, the water below the underdrain needs to drawdown in a 48 hour time period. The media below the underdrain has a porosity of 0.4 cubic feet per cubic foot. The following steps detail how this system would be set up in the MIDS calculator.

Step 1: Determine the watershed characteristics of your entire site. For this example we have a 1.8 acre site with 1.4 acres of impervious area and 0.4 acres of pervious turf area in type B soils. The impervious area includes the area of parking lot that has permeable pavement.


Screen shot of the Site Information tab for the permeable pavement example. See Step 2.

Step 2: Fill in the site specific information into the *Site Information* tab. This includes entering a Zip Code (55414 for this example) and the watershed information from Step 1. Zip code and impervious area must be filled in or an error message will be generated. Other fields on this screen are optional.


Screen shot of the Schematic tab for the permeable pavement example. See Step 3.

Step 3: Go to the Schematic tab and drag and drop the *Permeable Pavement* icon into the *Schematic Window*

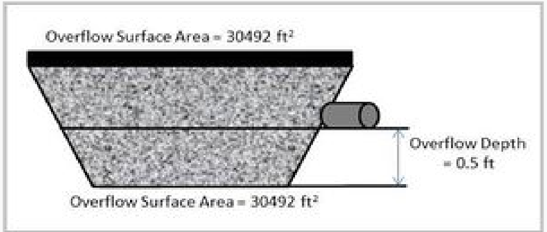
Step 4: Open the BMP properties for the permeable pavement by right clicking on the "Permeable pavement" icon and selecting *Edit BMP properties*, or by double clicking on the *Permeable pavement* icon. Click on the *Watershed* tab.

Step 5: If help is needed, click on the *Minnesota Stormwater Manual Wiki* link or the *Help* button to review input parameter specifications and calculation specific to the *Permeable pavement* BMP.

Step 6: Determine the watershed characteristics for the permeable pavement. For this example the entire site is draining to the permeable pavement. The watershed parameters therefore include a 1.8 acre site with 1.4 acres of impervious area and 0.4 acres of pervious turf area in B

soils. There is no routing for this BMP. Fill in the BMP specific watershed information (1.4 acres on impervious cover and 0.4 acres of Managed turf in B soils).

Step 7: Enter in the BMP design parameters into the *BMP parameters* tab. Permeable pavement requires the following entries:



Schematic showing inputs for the permeable pavement example. See Step 7.

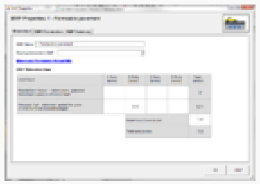
- Surface area at underdrain. This is the area of the BMP, which is therefore the area of the permeable pavement. This area is 0.7 acre or 30492 square feet.
- Bottom surface area, which is the area at the interface between the bottom of the permeable pavement system and the top of the underlying native soils. This area is 30492 square feet.
- The depth below the underdrain is 0.5 feet.
- The media porosity is 0.4 cubic feet per cubic foot.
- Will the soil require compaction – No.
- Underlying soil – Hydrologic Soil Group, which is 6 SM (HSG B, 0.45 in/hr).
- Required drawdown time, which is 48 hours.

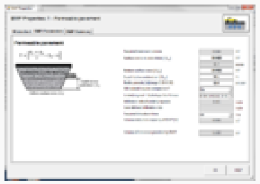
Step 8: Click on *BMP Summary* tab to view results for this BMP.

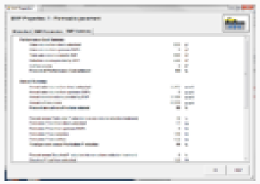
Step 9: Click on the *OK* button to exit the BMP properties screen.

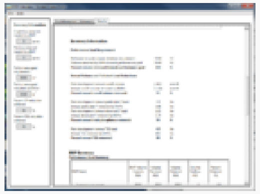
Step 10: Click on *Results* tab to see overall results for the site.

MIDS calculator screen shots for inputs for permeable pavement. Click on an image for enlarged view.


Screen shot of watershed tab for permeable pavement example. See Step 6.


Screen shot of BMP Parameters tab for permeable pavement example. See Step 7.


Screen shot of BMP Summary tab for permeable pavement example. See Step 8.


Screen shot of Results tab for permeable pavement example. See Step 10.

Requirements

Warning: The following are requirements of the Minnesota Construction Stormwater General Permit

- 3 foot separation from the bottom of an infiltration system to the seasonal high water table
- Use the most restrictive infiltration rate within 5 feet of the bottom of the BMP
- For measured infiltration rates, apply a safety factor of 2
- Pretreatment for infiltration systems

Recommendations

Caution: The following are recommendations for inputs into the MIDS calculator

- Drawdown time of 24 hours when the discharge is to trout streams
- Field tested infiltration rates rather than table values

Information

Information: The following information may be useful in determining inputs for the MIDS calculator

- Guidance on determining infiltration rates
- Information on site constraints (shallow soil, karst, etc.)
- Guidance on pretreatment
- Construction specifications for permeable pavement BMPs
- Information on operation and maintenance of permeable pavement BMPs.

Links to MIDS pages

- Overview of Minimal Impact Design Standards (MIDS)
- Performance goals for new development, re-development and linear projects
- Design Sequence Flowchart-Flexible treatment options
- Community Assistance Package
- MIDS calculator
- Performance curves for MIDS calculator

- Training and workshop materials and modules
- Technical documents

Categories: Construction specifications | Permeable pavement

MINNESOTA POLLUTION CONTROL AGENCY